Tensile and Fatigue Behavior of Structural Steel Plates with Slotted Holes

by

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Thesis

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

Master of Science in Engineering

The University of Texas at Austin
August 2006

Tensile and Fatigue Behavior of Structural Steel Plates with Slotted Holes

Approved by
Supervising Committee:

Karl H. Frank

Todd A. Helwig

Dedication

To Mira, my wife, for all the love and support.

Acknowledgements

The author would like to thank Dr. Karl H. Frank for his guidance throughout the research and thesis writing process. Special thanks are given to the staff of the Ferguson Structural Engineering Laboratory. Their suggestions and help were greatly appreciated and vital to the completion of the research project. Dr. Todd A. Helwig's help with the writing process was also appreciated.

August 2006

Abstract

Tensile and Fatigue Behavior of Structural Steel Plates with Slotted Holes

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This research is a continuation of a project sponsored by the Texas Department of Transportation (TxDOT) titled "Performance and Effects of Punched Holes and Cold Bending on Steel Bridge Fabrication." The first two phases of the project was presented by Lubitz (2005) in "Tensile and Fatigue Behavior of Punched Structural Plates" and by Brown (2006) in "Punched Holes in Structural Connections."

AASHTO does not allow full size punched round holes in primary load carrying members. The specifications state that holes in these members may be punched and then reamed full size (in order to remove the damaged zone immediately surrounding the hole) or drilled. The purpose of reaming is to remove the damaged material surrounding the hole and any micro-cracks formed during the punching operation. However, AASHTO Construction specifications do not specify which technique to be used for slotted holes, which is not consistent with round hole making specifications. Also, there isn't much information about the behavior of members with slotted holes and round holes created using thermal cutting in the literature under static and fatigue loads.

The goal of the main part of the project was to investigate the effects of different hole making techniques on the tensile strength and the fatigue behavior. Static and fatigue loads tests were done in Ferguson Laboratory to gain more information about the issue. Based on the results of this study, possible modifications of AASHTO and AISC specifications were developed.

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CHAPTER 1

Introduction

1.1 PROJECT DESCRIPTION

This thesis is part of a research investigation titled “Performance of Punched Holes and Cold Bending on Bridge Fabrication” ongoing in both University of Texas – Austin and Texas A&M University – College Station. It includes but is not limited to research done in the Ferguson Structural Engineering Laboratory (FSEL). The work presented herein addresses the influence of the process utilized in making slotted holes making process on the tensile strength and fatigue performance of steel plates. The study was divided in two parts 1) an investigation on the influence of different dies on the quality of the punched holes and 2) the influence of different hole making techniques for slotted holes on the ultimate tensile strength and ductility of plates with slotted holes.

1.2 EXPLANATION OF THE AVAILABLE HOLE MAKING TECHNIQUES

1.2.1 Punching

Punching is an economical and easy way to form holes in steel plates; however the method is also somewhat controversial. It was called a “barbarous” technique by the editor of The Engineer magazine (1864). This statement was caused mainly because of the appearance of the punched holes. The two holes shown in Figure 1-1 and Figure 1-2 show the better appearance of drilled hole relative to punched hole.

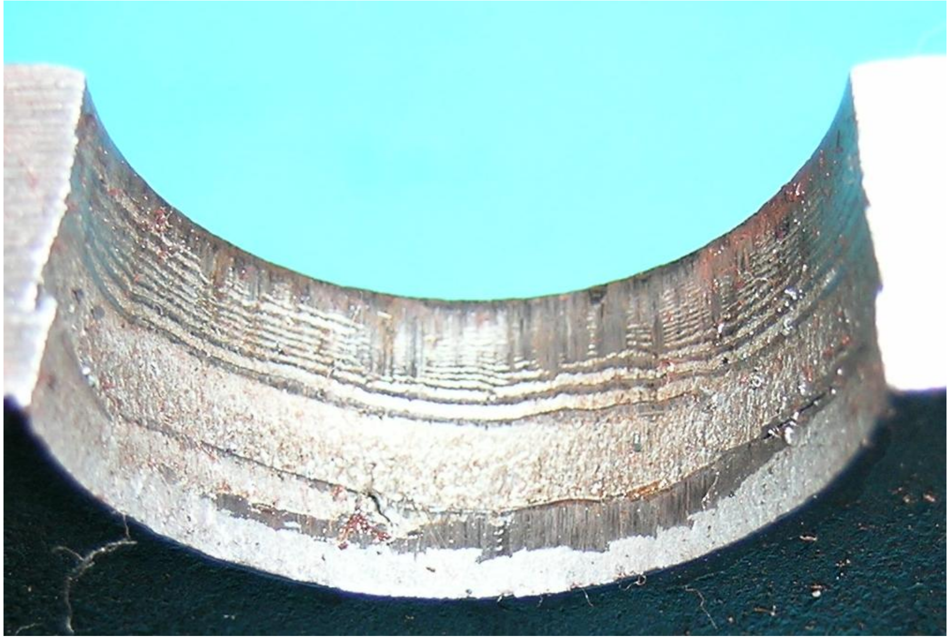


Figure 1-1 Typical punched hole

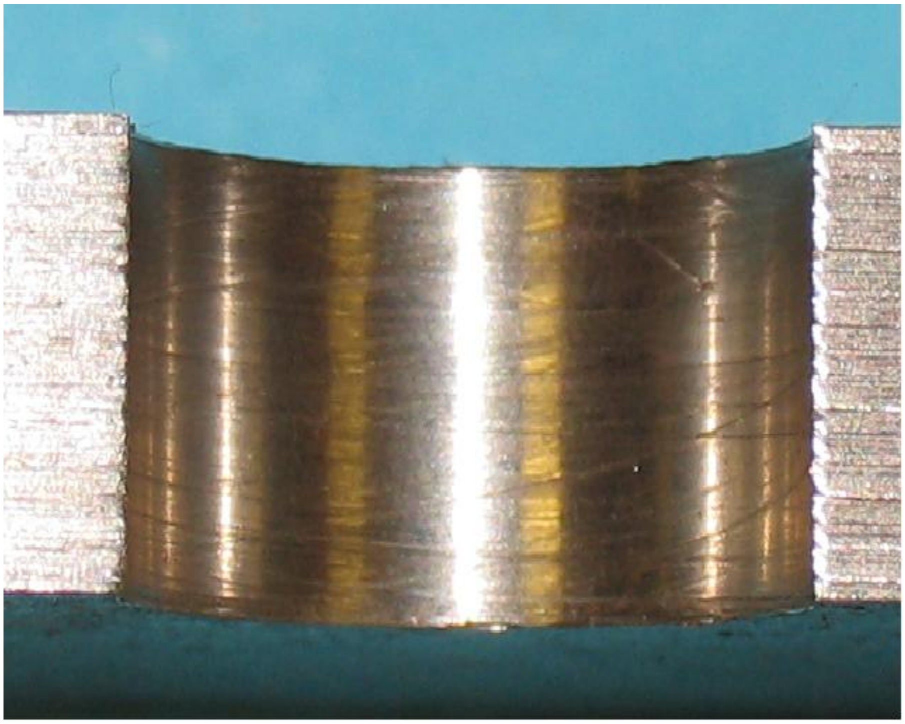


Figure 1-2 Typical drilled hole

Many studies have been made on the effects of hole making on the performance of steel connections. Munse and Chesson found that connections with drilled holes are better than connections with punched holes. Their argument was that when the punch penetrates the plate it creates microcracks in the material in the vicinity of the hole reducing the tensile strength capacity and ductility of the connections. On the contrary, others, like Owens suggested there is no difference in the strength of plates with drilled and punched holes. He claims that the reduction in strength, if any, is negligible and there is no need of banning the use of punched holes. In short, there is disagreement between the researchers on the use of punched holes should be used in steel construction.

Another limitation of punched holes is that it requires heavy equipment. Although portable presses are available, most punch presses are large and require the piece to be brought to the punch. For this reason, punching is preferred for small pieces of steel like angles or gusset plates. In bridges the most common use for punched holes are angles used for internal and external cross frames and lateral truss systems for box girders.

1.2.2 Drilling

Drilling of holes is the most common technique of hole fabrication. Although drilling is more expensive than punching, a better quality of hole is generally produced. Also, research by Polmear et al.(1971) showed that drilled holes have better behavior than punched holes when subjected to repeated loads and for that reason punched holes are not allowed in the primary members of bridges in many countries (AASHTO, British Specifications).

1.2.3 Reaming

Reaming is another regularly used way of enlarging holes and fitting plies in members that are subject to fatigue. Since all the bridge elements have to be shop assembled reaming is very convenient way to fit the pre-made holes. The hole that will be reamed is first sub-punched or sub-drilled with diameter 3/16” less than the required size. The holes that are going to be connected with one fastener are then assembled and the hole is reamed to full size. In addition to the perfect alignment of the holes, a major advantage of reaming is that the material damaged from punching is removed, which improves the ultimate strength and fatigue performance of the steel. Figure 1-3 shows a typical reamed hole.

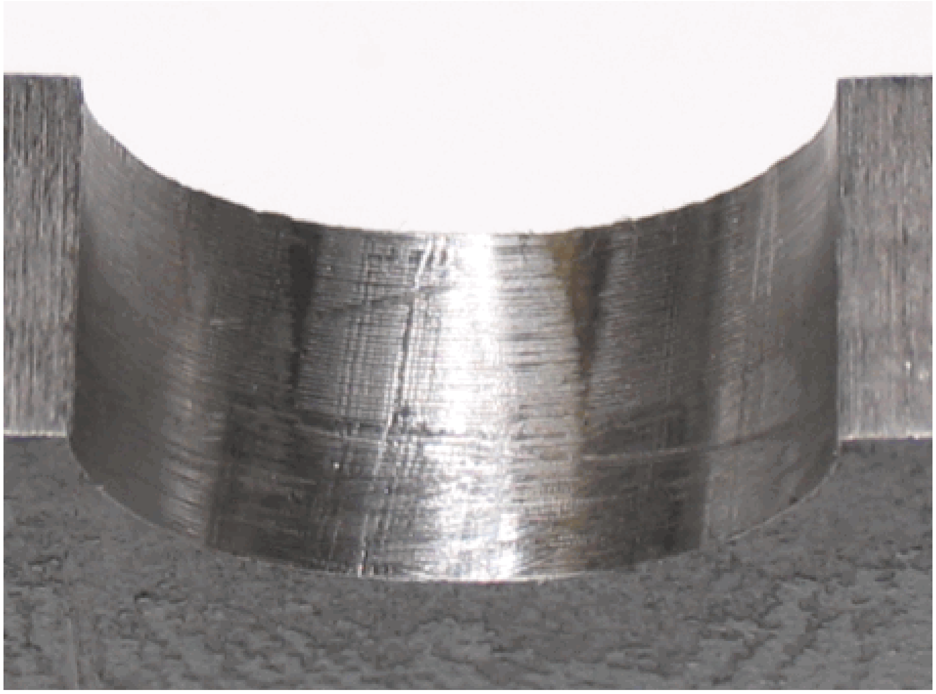


Figure 1-3- Typical reamed hole

1.2.4 Thermal cutting

Another hole-fabricating method is thermal cutting, which includes laser cutting, plasma torch cutting and oxy-act cutting. Oxy act stands for oxygen acetylene. The latter two are usually used on the construction site, because they are fast and easy ways to make holes and there is no need for special equipment other than that already on the construction site. Laser cutting, on the other hand, can be done only in the fabrication plant; however the holes that are produced have much better surface finish and dimensional accuracy than the holes produced by the other two techniques. Figure 1-4, Figure 1-5 and Figure 1-6 show typical thermally cut holes.

Figure 1-4 Typical oxy act hole

Figure 1-5 – Slotted plasma cut hole

Figure 1-6 – Slotted laser cut hole

1.2.5 Slotted Holes

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 the before- mentioned techniques. Examples of using only one hole-making technique are shown in Figure 1-6 and Figure 1-7.

Figure 1-7- 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 1-8 and Figure 1-9.

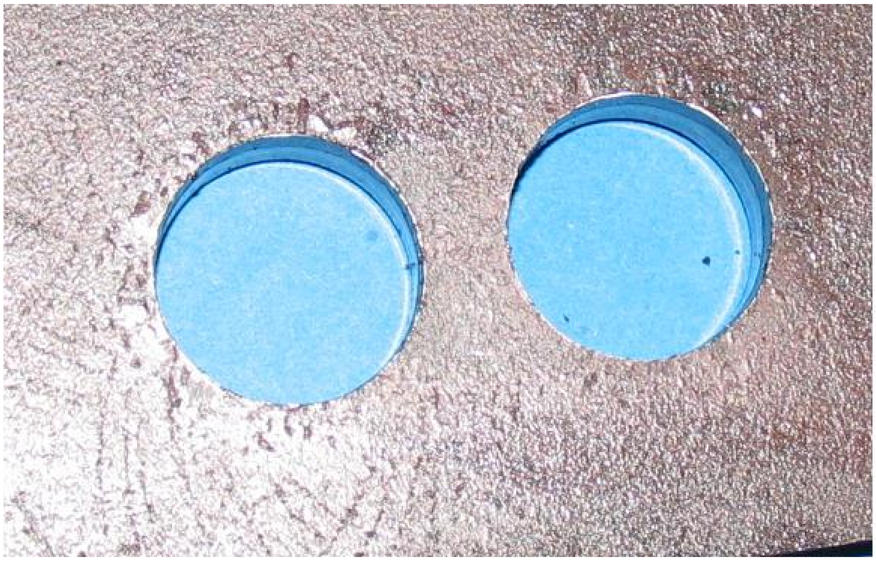


Figure 1-8- Both ends of slotted hole punched

Figure 1-9- Punched holes joined with oxy-act cut

1.3 PROBLEM STATEMENT AND SCOPE

AASHTO does not allow full size punched round holes in primary load carrying members. The specifications state that holes in these members may be punched and then reamed full size (in order to remove the damaged zone immediately surrounding the hole) or drilled. The purpose of reaming, as mentioned before, is to remove the damaged material surrounding the hole and any micro-cracks formed during the punching operation. However, AASHTO Construction specifications do not specify which technique to be used for slotted holes, which is not consistent with round hole making specifications. Also, the behavior of members with slotted holes and round holes created using thermal cutting in the literature under static and fatigue loads are generally not well understood.

The primary goal of this research study was to investigate the effects of different hole making techniques on the tensile strength and the fatigue behavior. Static and fatigue loads tests were conducted in Ferguson Laboratory to gain more information on the impact of the hole-making techniques on the structural behavior. Based on the results of this study, possible modifications of AASHTO and AISC specifications were developed.

To gain more knowledge about the force displacement relationship during the punching process, approximately 30 tests were conducted. The parameters of the tests included the type of steel, the thickness of the plates and the diameter of the die.

CHAPTER 2

Background and Literature Review

2.1 BACKGROUND

Punching is the fastest and the cheapest hole making technique that is available. However the method is generally limited to shop fabrication if a mechanical punch press because the press cannot be moved on the field due to its size. In addition, the process is also limited to relatively thin members. The shear action of the punch distorts the steel in the vicinity of the hole and leaves a cold-worked material around the perforation reducing its ductility and strength. For that reason, most of the current bridge fabrications standards allow full size punched holes to be used only on secondary members and require holes in primary members to be sub-punched and reamed to the full size. Reaming is used to remove the damaged material surrounding the hole. Interestingly enough, American Institute of Steel Construction (AISC) specifications do not distinguish between drilled and punched holes. More interesting is that for slotted holes even the AASHTO (bridge) specifications do not differentiate between drilled and punched holes.

2.1.1 Hole punching operation

The steel plate is set between the punch and the die and a force is applied on the punch. On the impact of the punch with the plate, vertical and horizontal forces are produced on the steel plate and as a result of those forces there are also reaction forces from the die. The combination of the moment produced from those forces and the shear acting on the plate cause the slug to separate from the steel. Figure 2-1 depict the forces acting on the plate.

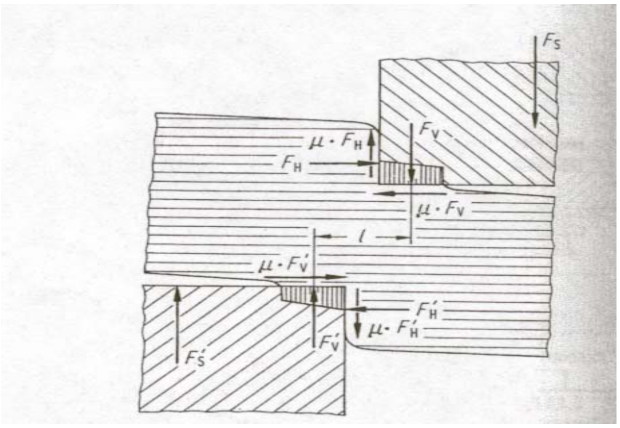


Figure 2-1-Action of forces in punching (Handbook of Mechanical Engineering, 1994)

2.1.2 Sequence of punching

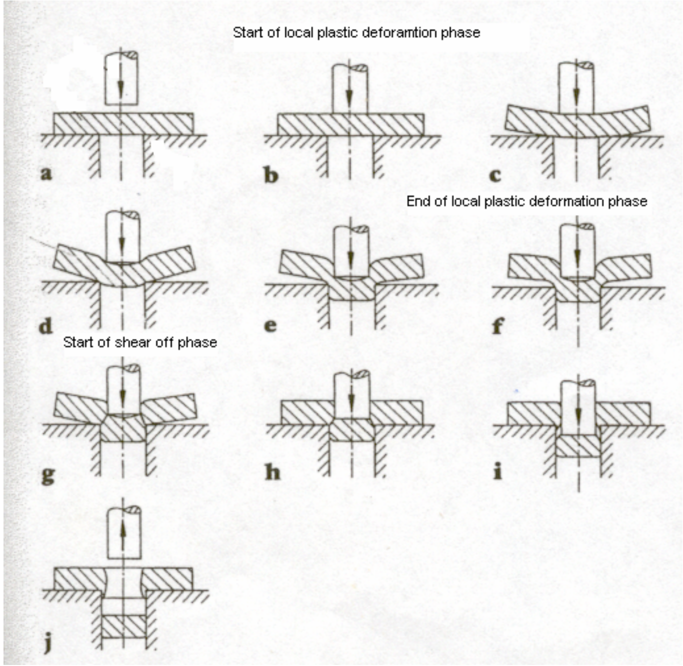


Figure 2-2-Sequence of punching (Handbook of Mechanical Engineering, 1994)

At the beginning of the punching process the plate bends under the punch and partly lifts off the face of the die. The plate then undergoes local plastic deformation producing a permanent bulging of the plate. In the next cutting phase the material is sheared off producing the smooth cut part of the cut surface. The tensile stresses increase in the cross section leading to the formation of the first crack starting from edge of the die. Further cracks then form in the plate at the edge of the punch. At the moment of cracking the maximum shear stress reaches the shear fracture point leading to cracking. The penetration of the punch in the plate at this point is approximately 0.1 inches. Three zones that are associated with the punching phases can be observed on the hole surface. The first zone is a result of the punch compressing the material underneath it and its surface is smooth. The second zone is the shear off zone – and it is rough and inclined. The third zone is a combination of the die compressing the material and the initial bending seen in part d of Figure 2-2. For this reason the hole is wider in zone 3 than in zone 1. The process also is described in W.A. Whitney's Operations Manual and Handbook of mechanical engineering (1994).

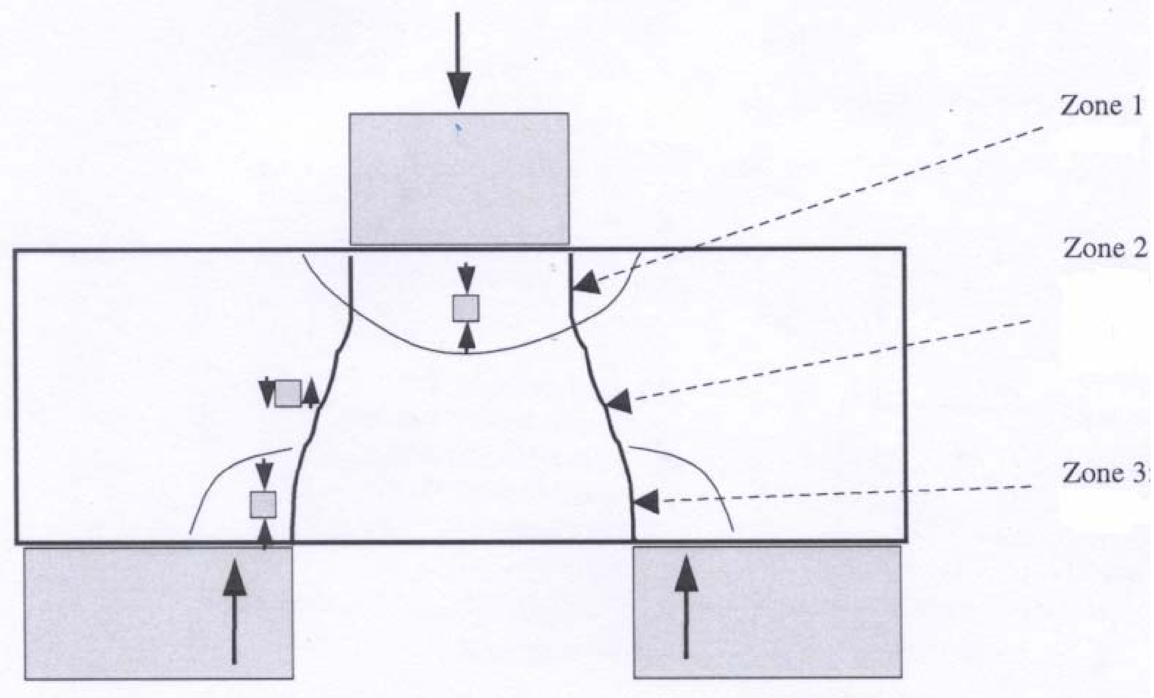


Figure 2-3 Different zones on punched hole surface (Sanchez et al., 2004)

2.1.3 Hole imperfections

Besides the roughness of the hole surface there are other defects, such as edge indentation and burr that occur when the holes are punched. Edge indentation is the dip in the material caused by the punch when creating the hole and while the burr is the material that rises outside of the plane of the plate as a result of the punch getting out of the steel plate. A rough picture of these defects is depicted in Figure 2-4.

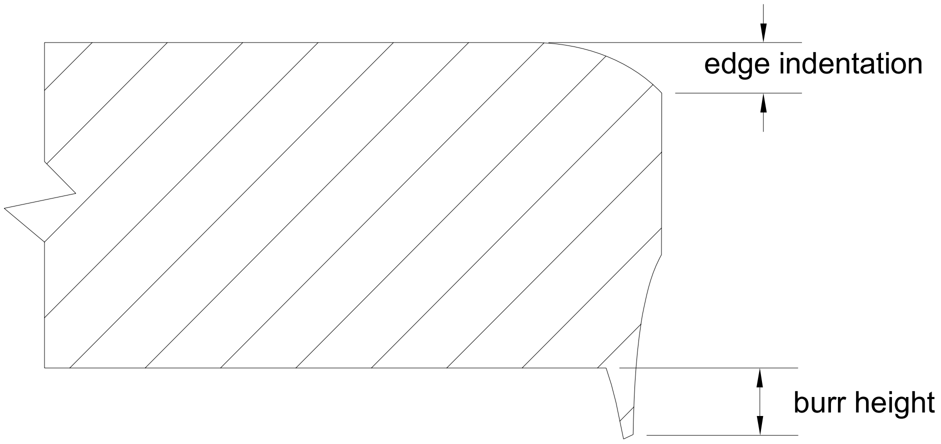


Figure 2-4 Hole surface imperfections

2.1.4 Proper die clearance

To limit defects such as edge indentation or burr height, producers of punch presses suggest certain clearances for different values of the material thickness. A rule of thumb is that the clearance should be approximately 15 % of the thickness of the material. Table 2-1 shows the clearances suggested by W. A. Whitney Corp. their punches.

Table 2-1

Material thickness	Die clearance
1/8” – ¼”	0.02”
¼” – ½”	1/32”
7/16” – 13/16”	1/16”
5/8” – 1-1/16”	3/32”
1” – 1-1/4”	1/8”

Inadequate clearance can cause excessive wear and produce secondary shear effects requiring the press to spend more energy. While this is not too significant of a consideration for hydraulic presses it is important for mechanical presses since their stored energy is limited. Figure 2-5 is an example how a force - deformation diagram should look like for a proper die.

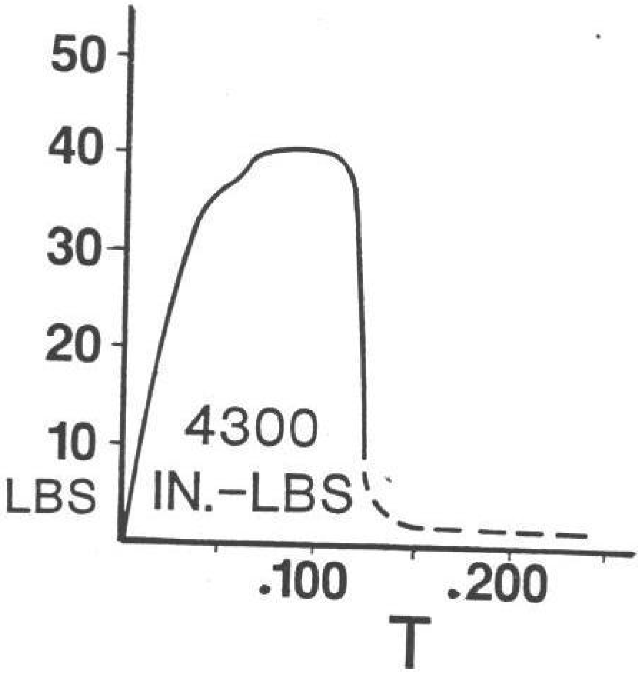


Figure 2-5 "Proper" die clearance force-displacement relationship (W.A.Whitney Operations Manual)

However, if the clearance is too small it wears the punch and shortened its life. See Figure 2-6 as an example of how force – displacement diagram looks when the clearance is less than prescribed. The energy required for punching is equal to the area under the curve. The resulting energy required with the inadequate die clearance depicted in Figure 2-6 is 7500 in-lbs, is almost twice than energy required with larger clearance depicted in Figure 2-5.

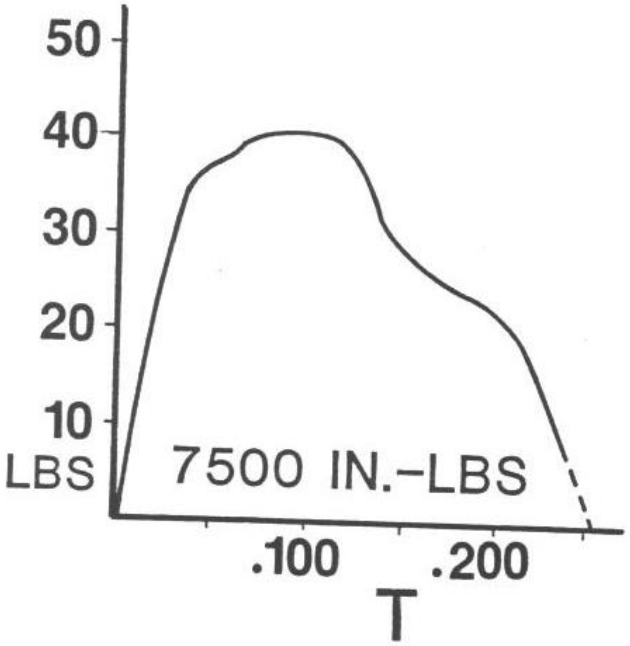


Figure 2-6 "Improper" die clearance force-displacement relationship (W.A.Whitney Operations Manual)

From the graphs it can be seen that the area under the curve is larger when the die clearance is smaller. This energy is spent to punch a hole. As a mentioned before this is important for mechanical presses because they store energy before the start of punching and if there is not enough energy they are not going to be able to punch through the material. Another important observation that can be made is that the shapes of the curves for both cases are different. The "proper die" curve after the peak drops to zero resistance is a straight line. In the "improper die" curve there is a hump after the peak load. This hump is caused by the secondary shear that the punch has to go through.

The amount of the force needed for a plate to be punched depends on:

- the diameter of the hole
- the thickness of the plate

- the strength of the steel

The companies that produce punching presses usually provide guidelines for the force required based upon the material to be punched. Handbook of Mechanical Engineering (1994) mention that the following formula is used in Germany:

$F_{max}=0.8F_u t\pi d$, where

t – the thickness of the plate

d – diameter of the hole

F_u- ultimate strength of the steel

The other issue that is affected by the clearance is the roughness of the hole. Figure 2-7 is an example of the resulting hole roughness that occurs when insufficient die clearance is used.

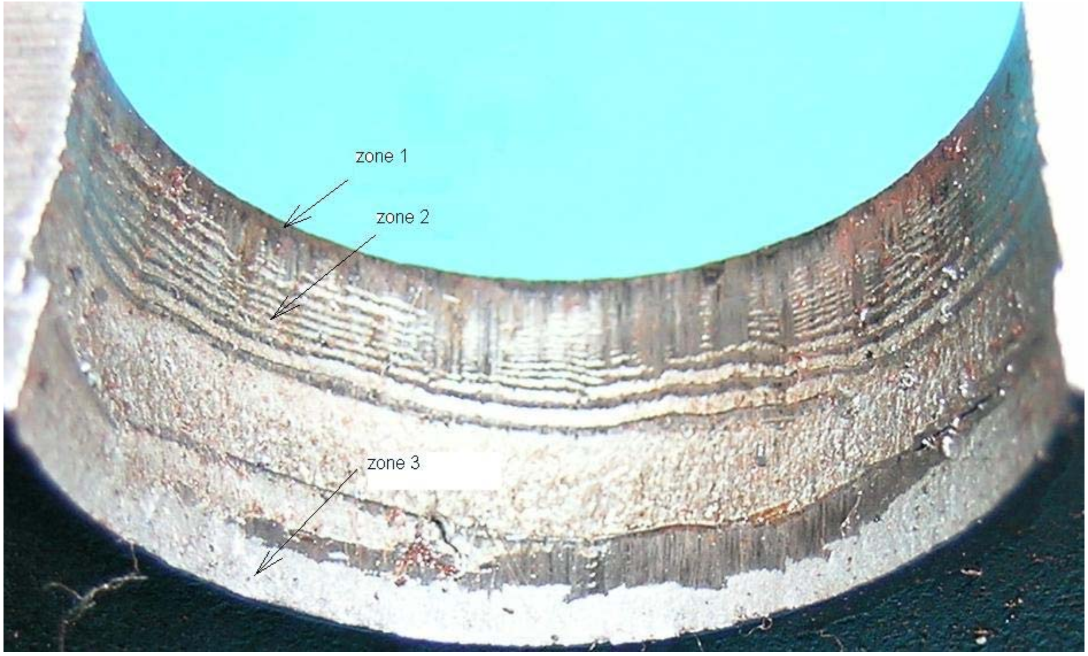


Figure 2-7 –Surface of a hole made with insufficient die clearance

A die with excessive clearance causes deformation, burrs and a noticeable fracture angle. In addition to poor hole quality, tool life decreases and breakthrough shock increases with large clearance. Typical hole surface of large clearance can be seen on Fig 2-8.

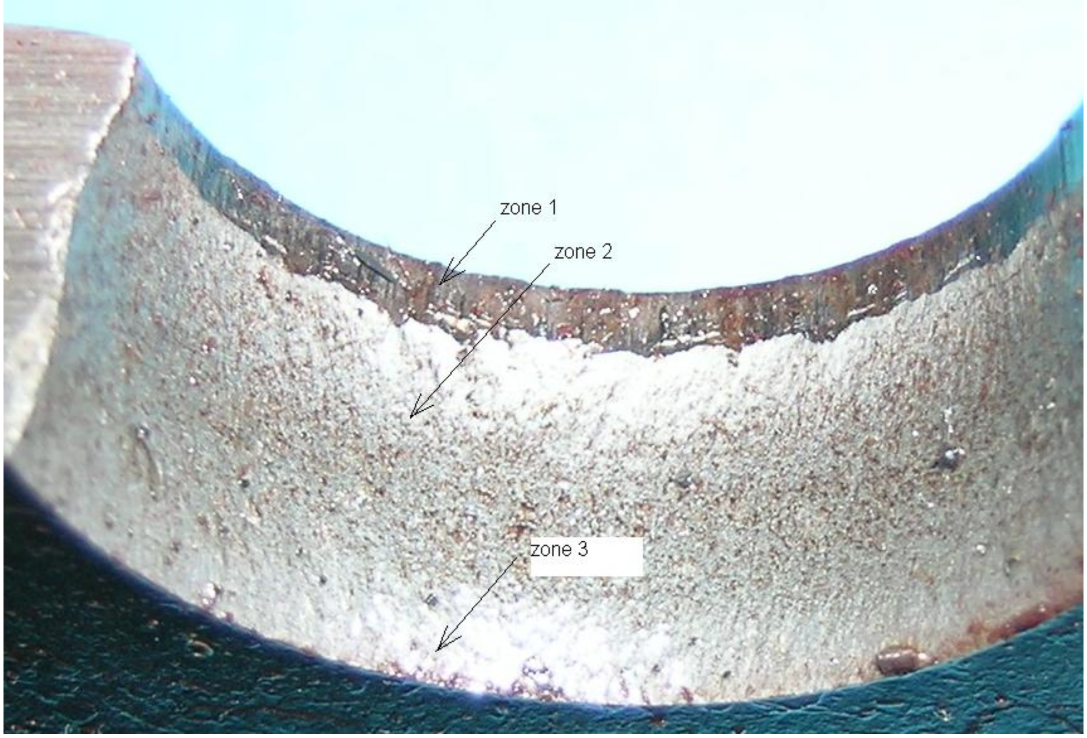


Figure 2-8- Surface of a hole made with too large die clearance

2.2 LITERATURE REVIEW

2.2.1 Ultimate strength and ductility

The first available publication related to punched holes appeared in a publication called "Engineering" (1881) that summarized a series of 12 tests. The article found three principle facts:

- drilled specimen have higher tensile strength than the punched
- damaged material from punching can be removed by reaming

- and, thicker plates were damaged more by punching than the thinner plates.

In 1959 another research paper on different fabrication techniques was published by Vasarhelyi et al. Double lap tensile splices with one or three rows of four bolts were tested. Besides the hole preparation (drilled or punched) the parameters of the study were surface treatment (mill scale or red lead paint), test temperature (room temperature and -25 F) and transverse hole distance. The bolts were pretensioned and designed to work as slip – critical. The observed failure was as follows:

- ductile net area yielding was observed for the drilled holes at room temperature and -25 F;
- ductile net yielding was observed for most of the punched holes at room temperature;
- brittle failure was observed for the punched holes at -25 F
- The summary stated that punching reduction in strength by 10% and reduction in ductility by 40% and the reduction in strength and ductility of the punched holes specimen tested in -25 F was 25% and 40 % respectively.

Around the same time as the Vasarhelyi study, Chesson and Munse (1959) tested riveted and bolted holes which were either drilled or punched. Their test set up consisted of angles connected to gusset plates with two lines of seven bolts or rivets. Although the failure was expected in the net area of the angles the actual failure occurred at the gusset plate. For the drilled specimen the failure occurred by ductile tearing along the net area section; however in the punched specimen this tearing was followed by splitting along the bolt line. The net section failure of the gusset plate is shown in Figure 2-9.

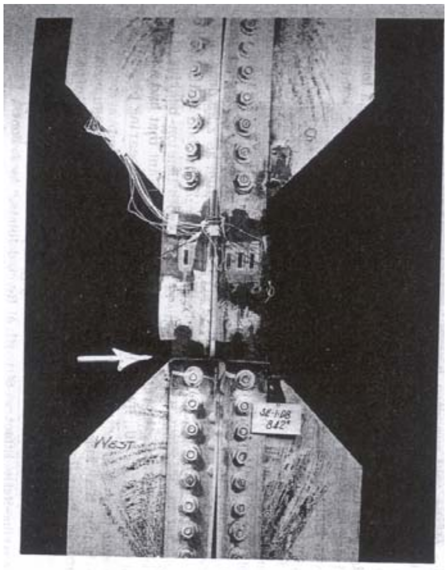


Figure 2-9- Typical net section failure of Munse's et al specimen

The tensile strength capacity of bolted specimens with the punched holes reached only 95 % of the corresponding values of those with drilled holes. The corresponding strengths of riveted specimens with punched holes were between 90 and 95 % of the corresponding values with drilled holes. Unfortunately, the ductility in both cases was not reported.

Owens et al (1981) cites a study on drilled and punched holes made by Epstein in 1932 as the first extensive investigation of the 20th century of the galvanizing on the embrittelment of plates in which bolted holes were made by punching. Epstein used various tests to determine the extent to which punching decreased the ductility of the plates. He found that the ductility of the punched specimen decreased when the thickness of the plates increased, and it was always less than the corresponding ductility of the plates with drilled holes. However, the hole size to thickness ratio changed from 2.75 to 4.5 for thinner angles to 0.94 to 1.58 for thicker angles which raises a question whether a combination of factors, and not only the size, caused the brittle failure of the larger angles.

Another report used by Owens in his literature review was an investigation in Sweden made by Wallin (1975) upon the influence of the hole forming process on the tensile strength of plates connected with fasteners working in bearing and shear. The punched holes were made with different punching techniques including hydraulic press, yield punching and high speed punching. Those were compared with drilled and reamed holes specimen. The reported reduction in tensile strength of the connections made by punching was 10 % when compared with drilled or reamed and the reduction in ductility was 10 to 50 %.

Owens et al (1981) were more interested in the effects of strain aging and therefore many of the specimens were tested 6 months after they were fabricated. Only one specimen was tested within 2 weeks of fabrication. He reported that the bearing stress (ultimate tensile strength) was higher for the punched holes than for the drilled holes, which is just opposite to the findings from all the previous studies. The explanation was that this is due to better punching techniques that are available but later results did not confirm that. The other reason that he suggested was that he used different steels for the specimen with punched holes and with drilled holes and that probably the bearing strength depends not only on the mechanical properties but on secondary properties of the steel. The ductility however was mostly in agreement with the results of the previous studies and for punched hole specimen was between 38 and 80% of the drilled holes specimen, and there was one punched specimen that had higher deformation capacity than the drilled one.

In 1982 Iwankiw et al compared six different hole-making techniques in terms of ultimate tensile strength and ductility. Their test set up consisted of a single hole double lap connection using prestensioned bolts. However the slip load was approximately 30 % of the ultimate load so at the failure load the bolts were working in shear and bearing. Six techniques were investigated including: 1) punching, 2) punching and grinding the burr, 3) sub-punching and reaming, 4) drilling, 5) sub-flame cutting and reaming and 6) flame cutting. The AASHTO Specifications currently allow only two methods: 1)sub-punching and reaming and 2) drilling. Three specimens were tested in each case. Based on test results Iwankiw et al concluded that there is no significant difference in the ultimate tensile strength of the connection formed using the different techniques. However, in analyzing the data from this study, failure was not observed in some of the experiments due to limitation in the testing machine. The tests that didn't fail include two of the drilled specimens, one of the punched and reamed specimen, and one of the flame cut and reamed specimen.

In 2002 an investigation on hole making practices was made by Swanson et al. The used techniques that were investigated consisted of drilling, good punching, bad punching and flame cutting. Most of the flame cut holes were ground and only two were left ”as is”. Figure 2-10 represents the typical test set up utilized.

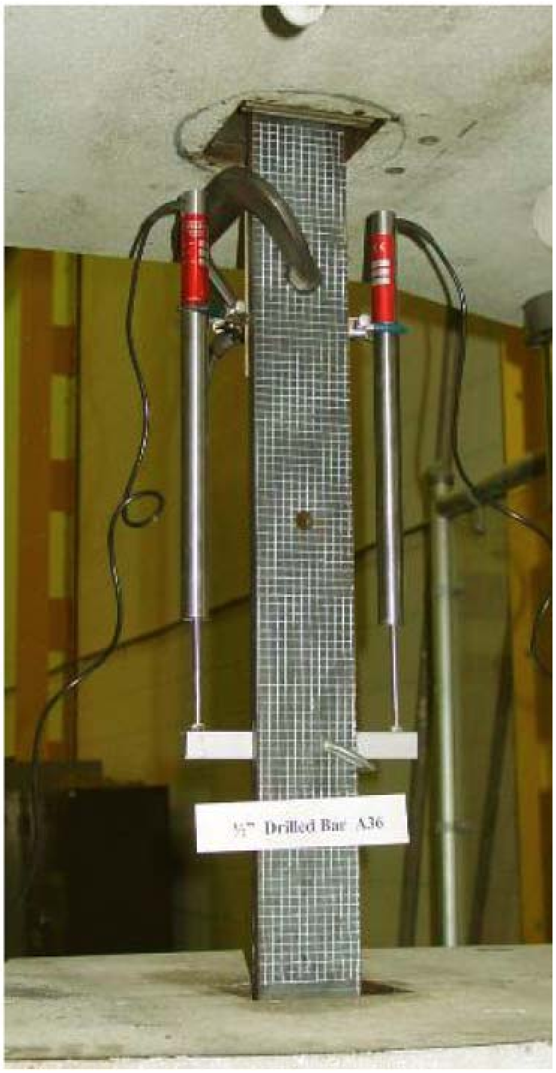


Figure 2-10 Typical test set up

Two different punch and die sets were used due to concerns of the importance on the wear of the punch and die on the ultimate tensile strength and the ductility of the plates. One of the punch and die set was relatively dull – and was labeled “bad punch” while the other punch and die set was relatively new – and was labeled “good punch”. The other two parameters considered included the hole sizes and different types of steel.

The strength ratio between punched and drilled holes is between 0.9 – 0.98 which is in agreement with the previous researches findings. The study reported no significant difference between good punched and bad punched holes. Another interesting fact is that with increasing the strength of the steel the difference between the ultimate strength of plates with punched holes and drilled holes decreased. The same tendency was observed in the results reported by Brown (2006). No explanation of this phenomenon has been found and additional research may be necessary. Another interesting fact is that flame-cut holes specimens have almost the same and sometimes higher tensile strength capacity than drilled holes – this is most likely of the grinding which removed most of the damaged material. The ductility ratio of the punched holes to the ratio of drilled again were in agreement with previous researches. The ductility of the punched holes specimens were 30 to 90 % of the ductility of the drilled holes specimens. The ductility of the flame-cut holes specimens ranged from 56 – 103 % of the specimens with drilled holes.

2.2.2 Fatigue

There has been relatively little work done difference of the fatigue behavior of plates with drilled and punched holes. The first one is cited by Owens and is made by Polmear et al. (1971). Polmear tested simple tensile splice and the parameters with respect of hole preparation technique, method of bolt tightening, type of bolts and effects of galvanizing. The behavior of specimens with reamed holes was found to be independent from the initial hole producing technique – be it is punched or drilled. Punched holes specimens had less fatigue life than the reamed. However, the difference between the fatigue lives decreased when the bolts were tightened up as seen in Figure 2-11 and for stresses ranges less than 20 ksi, it is practically unsubstantial.

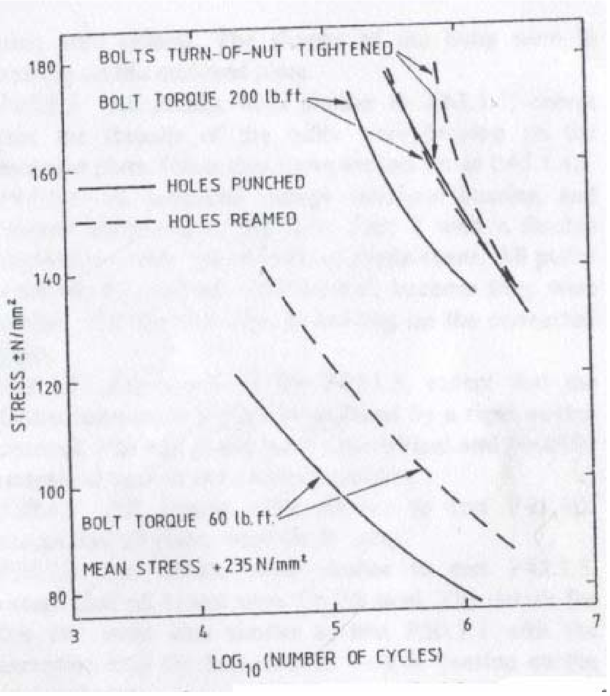


Figure 2-11 – Stress range vs. number of cycles relationship (Owens et al, 1981)

The improvement of the fatigue life is due to compression stresses applied from the bolt on the plates which help to arrest the micro-cracks that are created by punching the material. Leweitt et al. (1963) also observed the improved fatigue life that resulted from the larger compressive stresses in the plates caused by the use of high strength bolts.

In the recent years there are have been several studies in Europe and the USA on the fatigue performance of bolted connections. Sanchez et al (2004) tested 2 inch wide plates with a 5/8" hole in the middle. The conclusions were that drilled holes plates are superior to the punched holes plates. Initiation sites are localized at the punched hole surface in the transition region between zones 1 and 2 where maximum surface roughness was observed.

As a part of the same project Alegre et al (2004) conducted finite element simulation of the fatigue behavior of punched and drilled plates. The conclusion, based on the FEM results, was that the initial crack size of punched holes is between 0.25 – 0.5 mm (0.01 – 0.02”) and for drilled holes plates 10 times smaller.

Another recent study by Valtinat and Huhn (2004) investigated the influence of galvanizing, punching and high strength bolts on the fatigue life of structural steel plates. The tests indicated that the fatigue life of steel plates was reduced significantly by galvanizing and punching. However, repeated tests with tightened high strength bolts showed that there is no difference in the fatigue life between the specimens with drilled and punched holes.

At the same time research by Swanson et al (2004) confirmed that plates with punched holes have less fatigue life than plates with drilled holes. The specimens that were tested consisted of steel plates with three holes in a row. The hole diameter varied from 15/16” to 1 1/4” and the thickness of the plate from 5/8” to 1 1/8. The results demonstrated that besides the different hole making techniques the other parameters do not influence the fatigue life of steel plates.

Recent research carried out at UT Austin (Lubitz, 2005 and Brown, 2006) compared the influence of punched and drilled holes on the ultimate strength, ductility and fatigue life of steel plates and connections. Other variables that were considered included plate thickness, steel type, hole size as well as the size of die clearance. As before, the fatigue performance of bare plates with drilled and reamed holes was much better than plates with punched holes. Other observations from the study were that the fatigue behavior of the plates were not a function of the thickness of the plates, the ratio of hole diameter to the thickness of the plate, or the quality of the punched holes. Brown (2006) also compared the effects of the quality of the drill bits on the fatigue behavior. He observed that the fatigue behavior of holes made with worn or dull drill is almost the same as for steel plates with punched holes. However, as observed in previous studies, the adverse effects on the fatigue performance were offset with the use of connection with highly stressed bolts.

CHAPTER 3

Investigation of the punching process

3.1 INTRODUCTION

In order to get better understanding of the hole-punching process a study was inducted to investigate the force versus punch displacement relationship. The study examined the influence of different parameters on the force – displacement relationship and the quality of the holes.

3.2 TEST SET UP AND PROJECT MATRIX

A W. A. Whitney hydraulic punching press was used. The maximum pressure that was allowed for this press was 5000 psi. This punch was the same punch press and punch that were used for the ultimate strength and fatigue tests performed by Lubitz (2005) and Brown (2006) as part of the same project. The plates were punched with the same, 15/16”, size punch. The use of the same punch and punch press enabled similar imperfections to occur in the different punched holes specimens. The force during the punching process was obtained be measuring the hydraulic pressure and multiplying by the corresponding ram area. A linear potentiometer was attached to the punch to measure the displacement during the punching process. The test set up is shown in Figure 3-1.

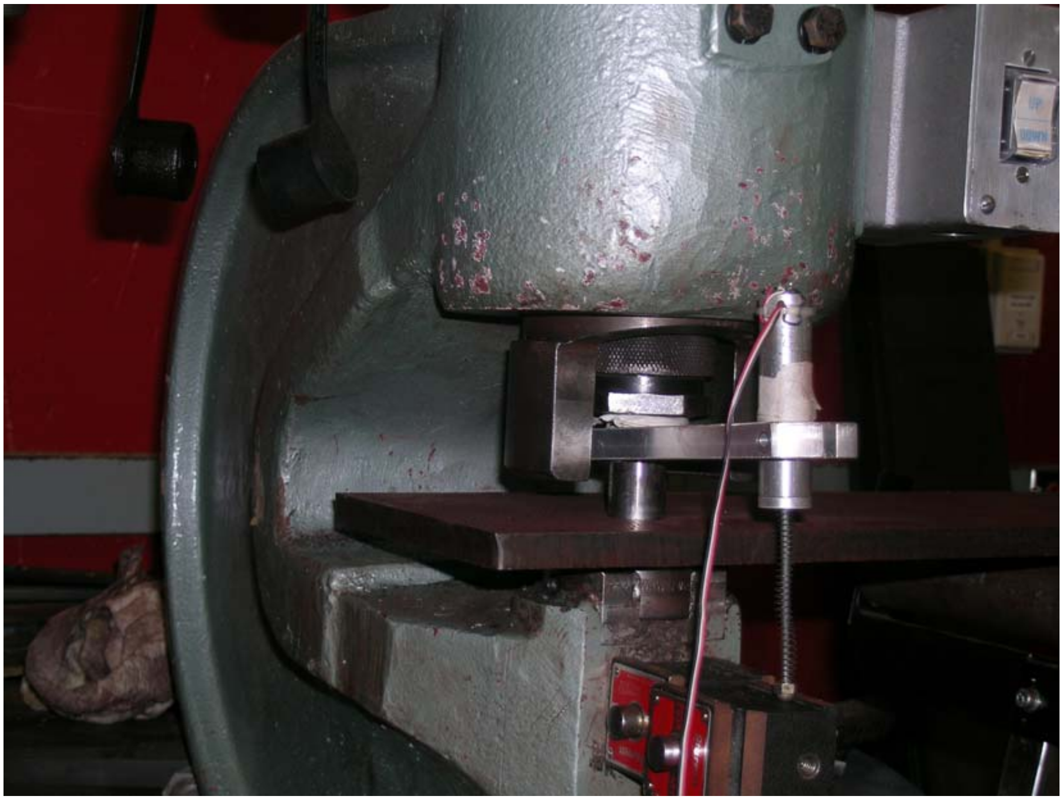


Figure 3-1Test setup

The test parameters included: plate thickness, steel grade and die clearance. Only one parameter was changed at a time so the influence of each could be monitored. The names and parameters of all the specimens are listed in Table 3-1.

Table 3-1 Project Matrix

Name	Steel grade	Thickness	Die clearence	Yielded
331531	A36	3/8"	1/32"	No
331532	A36	3/8"	1/16"	No
341531	A36	1/2"	1/32"	No
341532	A36	1/2"	1/16"	No
341533	A36	1/2"	3/32"	No
341531y	A36	1/2"	1/32"	Yes
341532y	A36	1/2"	1/16"	Yes
341533y	A36	1/2"	3/32"	Yes
361531	A36	3/4"	1/32"	No
361532	A36	3/4"	1/16"	No
361533	A36	3/4"	3/32"	No
381531	A36	1"	1/32"	No
381532	A36	1"	1/16"	No
381533	A36	1"	3/32"	No
531531	Grade 50	3/8"	1/32"	No
531532	Grade 50	3/8"	1/16"	No
5415312	Grade 50	1/2"	1/32"	No
541532	Grade 50	1/2"	1/16"	No
541533	Grade 50	1/2"	3/32"	No
561531	Grade 50	3/4"	1/32"	No
561532	Grade 50	3/4"	1/16"	No
561533	Grade 50	3/4"	3/32"	No
581531	Grade 50	1"	1/32"	No
581532	Grade 50	1"	1/16"	No
581533	Grade 50	1"	3/32"	No

Three additional tests were made with plate that had been loaded beyond its yielding point in order to determine if cold-working impacted the force - displacement relationship.

3.3 MATERIAL PROPERTIES

In total, there were 8 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 displacement during testing was monitored by an extensometer with an 8 in. gage length section. The load versus displacement relationship was recorded using a digital data acquisition system. The results from the coupon tests and the values from the mill test reports of each of the eight steel types are presented in Table 3-2. As indicated in the table, the measured values are given in bold on the first line for each heat description.

Table 3-2 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” Gr. 36	**39.5**	**64.7**	**38**	**0.611**
	na	*na*	*na*	*na*
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” Gr.50	**na**	**na**	**na**	**na**
	52.1	*72.4*	*29.4*	*0.72*

Coupon test results from Ferguson Lab values listed in bold

3.4 TEST RESULTS AND ANALYSIS

The influence of the different parameters will be introduced in the following order.

- Influence of the steel
- Influence of the yielding of the plate
- Influence of the die clearance and thickness of the plate

3.4.1 Influence of the steel grade

The purpose of this part of the project is to clarify the relationship between the maximum force needed to punch a hole and the yield strength or ultimate strength of the same die clearance and same plate thickness. Figure 3-2 represents a typical force versus displacement curve for two different steel strengths. The only difference between the two curves is that the grade 50 curve reached a higher force than the A36 curve. In addition to possessing a similar shape curve, the maximum force occurs at the same displacement for both steel grades.

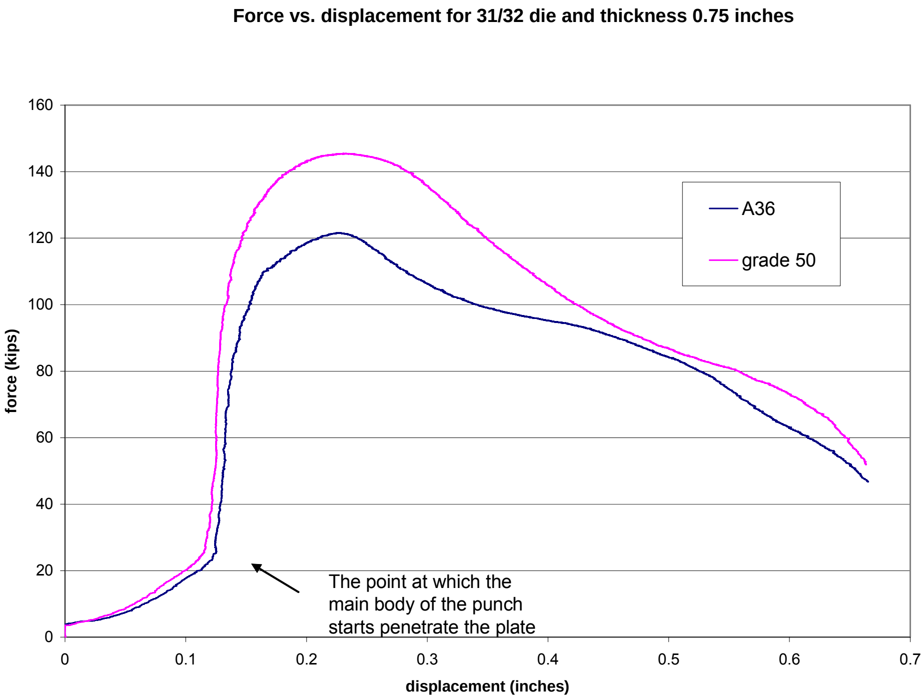
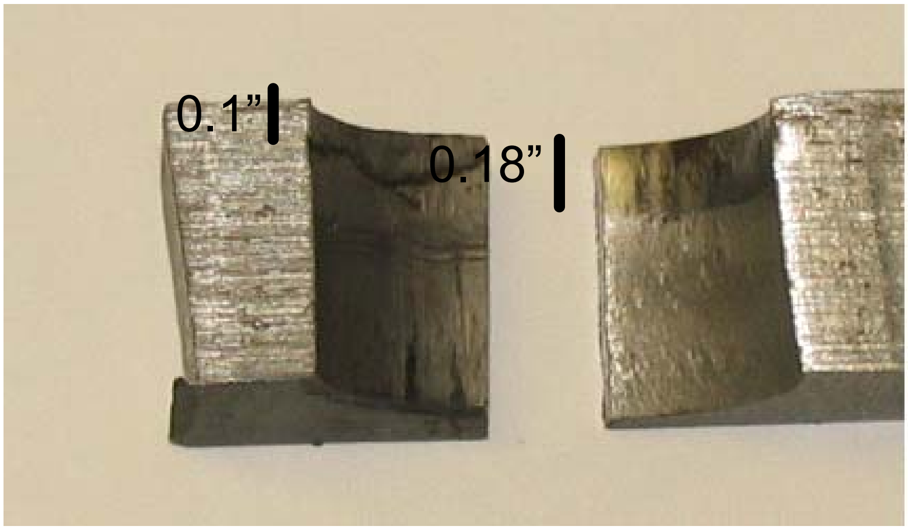


Figure 3-2 Punch force vs. displacement 31/32 die diameter and 0.75'' plate thickness

The kink in the curves at a displacement of approximately 0.125 in. occurs when the main body of the punch starts to penetrate the plate. Over the first 0.125 in. of displacement the tip of the punch that is used to align the punch and the hole penetrates the plate. Figure 3-3 shows the tip and punch face.

Figure 3-3Punch

The displacement at ultimate load is the same for both steels graphed in Figure 3-2 and was between 0.1 and 0.18 inches for all the specimens that were tested. The distance increases with the die clearance as can be seen in Figure 3-4. This initial loading represents zone 1 shown on Figure 2-3. Sanchez et al suggested that it is result of the shearing of the material by the contact of the punch and the steel plate.



1/32” die clearance

3/32” die clearance

Figure 3-4 Typical hole appearance made with larger die

A major consideration for a steel shop that is purchasing a punch press is the maximum steel plate thickness that can be punched with the press. Most punch press manufacturers provide tables with suggested “shear strengths” (F_{sh}) gained from experience for different materials. Also the maximum force can be compared with the yield strength and ultimate strength of the material. Table 3-3 contains all the results from the tests and comparison with the F_y, F_u for the steel and F_{sh} suggested by Whitney for A36 steel – which is 60 ksi.

Table 3-3 shows that the suggested shear strength is relatively close to the experimental results. The experimental results are from 90 to 100 % of the suggested values provided by W.A Whitney for the maximum force for A36 steel. The average of the values using F_{sh} for A36 steel is 0.95 and the standard deviation is 0.067.

Table 3-3 shows little correlation between the yield strength of the steel and force needed to punch a hole. The ratio between the experimental force and the yield strength times the hole area varies from 1.05 for grade 50 steel to 1.31 for A36 which is relatively large range. The average of the values when using F_y for A36 steel is 1.3 and the standard deviation is 0.13. For Grade 50 the values the respective values are 1.11 and 0.067.

The ultimate strength values are very close to 0.8 for both steels. This value is the same as the value cited in the Handbook of Mechanical Engineering (Handbook of Mechanical Engineering, 1994). The average of the values when using F_u for A36 steel is 0.84 and the standard deviation is 0.046. For Grade 50 the values respective are 0.81 and 0.032. This numbers also prove the consistency of the values using F_u.

Because of its broader application and the accurate prediction of the maximum expected punch force, F_u is better to be used for determining the maximum expected punch force than F_{sh}.

Table 3-3 Test results and comparison with F_y, F_u, F_{sh}

	Name	experimental force	test/π*d*t*Fy	test/π*d*t*Fu	test/π*d*t*Fsh
		kips			
A36	331531	64.92	1.24	0.83	0.98
	331532	63.06	1.20	0.81	0.95
	341531	83.61	1.20	0.81	0.95
	341532	81.41	1.16	0.79	0.92
	341533	82.07	1.17	0.80	0.93
	361531	122.06	1.31	0.84	0.92
	361532	119.44	1.28	0.82	0.90
	361533	118.7	1.27	0.82	0.90
	381531	176.07	1.51	0.93	1.00
	381532	171.74	1.48	0.90	0.97
	381533	173.87	1.49	0.91	0.98
Grade 50	531531	67.19	1.09	0.78	Na
	531532	66.85	1.08	0.77	Na
	541531	88.67	1.08	0.84	Na
	541532	87.56	1.07	0.83	Na
	541533	86.17	1.05	0.82	Na
	561531	145.06	1.08	0.79	Na
	561532	142.56	1.06	0.77	Na
	561533	141.58	1.05	0.77	Na
	581531	182.71	1.23	0.86	Na
	581532	180.08	1.22	0.84	Na
	581533	177.07	1.20	0.83	Na

3.4.2 Influence of cold working

This part of the investigation was made to clarify if the ultimate force and the relative displacement are a function of the material yield strength as well as the impact of cold working of the plate prior the punching. To get the force versus displacement curve a half inch thick steel plate was loaded to the yield stress and than punched. Figure 3-5, Figure 3-6 and Figure 3-7 compare the regular plate and yielded plate punch force curves for three different die clearances. It can be seen that the difference between the two is very small and is evident that the yielding strength is generally not a factor for the ultimate punching force needed.

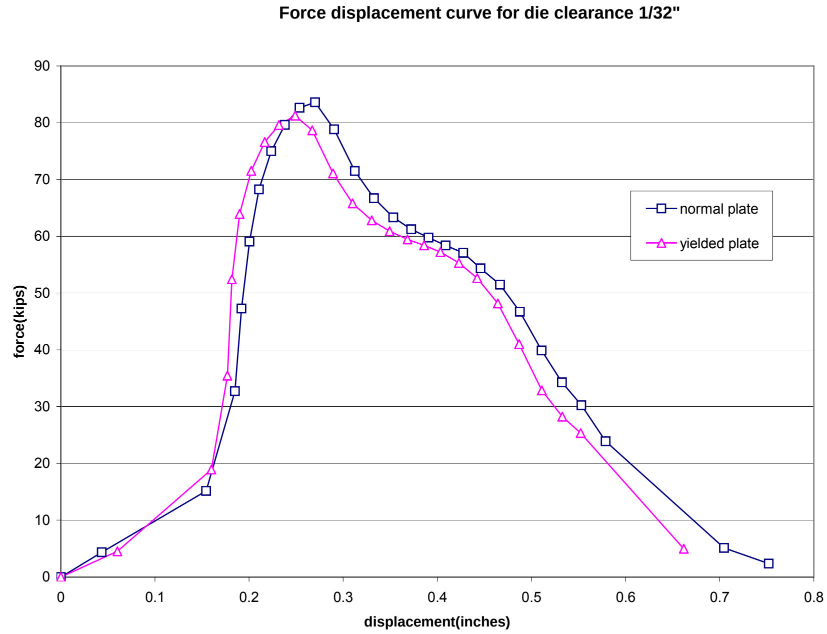


Figure 3-5 Curves for yielded and regular plate- die clearance 1/32"

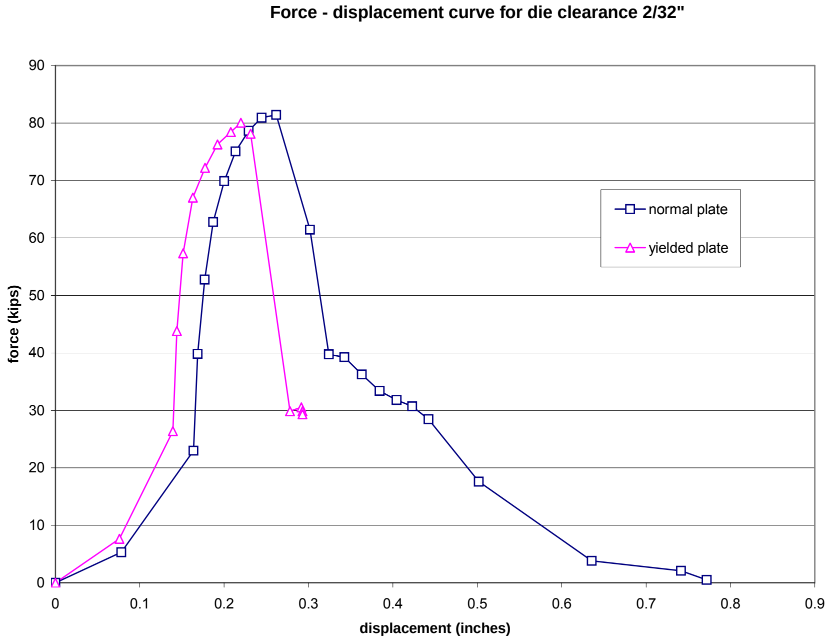


Figure 3-6 Curves for yielded and regular plate- die clearance 2/32"

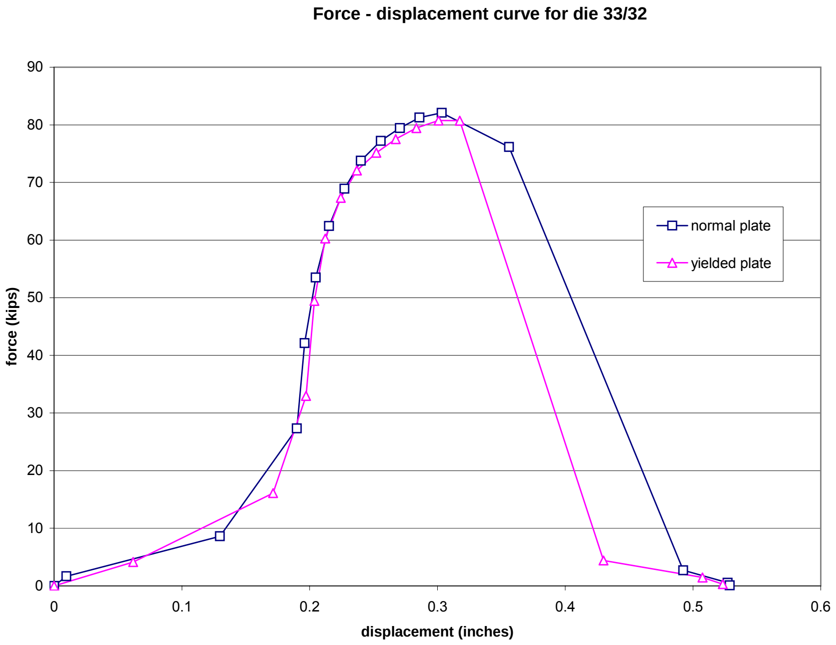


Figure 3-7 Curves for yielded and regular plate- die clearance 3/32"

3.4.3 Influence of thickness of the plate and the die clearance

These two parameters are investigated together since different types of holes were observed for different values of material thicknesses with the same die clearance. For example for 3/8" steel plate 2/32" clearance is excessive and it bending of the plate was observed resulting in a large burr. On the contrary, for ¾" plates 2/32" clearance was insufficient and produced secondary shear on the hole surface. Based upon these different behaviors, punch press manufacturers recommended die clearances as a function of the thicknesses as shown in Table 2-1.

3.4.3.1 Same die clearance - different thicknesses

As it was mentioned before the same die clearance produces different holes in different steel thicknesses. In addition, the force vs. displacement curves also differ as a function of the die clearance and material thickness. Figure 3-8 represents force vs. displacement for 1/32 die clearance for four different plate thicknesses. According to the W.A.Whitney's charts 1/32" die clearance is appropriate for 3/8" and ½" steel plates. The 1/2" thickness is at the limit between 1/32" and 2/32" die clearances. However, the graph for 3/8"thick steel looks like the graph from Figure 2-6 which is example of insufficient clearance. For the larger thicknesses the graphs look alike and have the same shape after the peak load.

Curves for the 1/16" die clearance are graphed for the same four thicknesses in Figure 3-9. This clearance according to the Whitney's charts is appropriate for ½" and ¾" thick plates. The graph for 3/8" thick steel has a rapid drop in load after the peak. During the test a shock sound was heard as the punch went through the plate along with a jump of the punch press, which are signs of using too large of a die clearance. However, the appearance of the holes made in 3/8" thick plate with larger clearance were smoother than the one made with the recommended 1/32" clearance shown in Figure 3-10 and Figure 3-11.

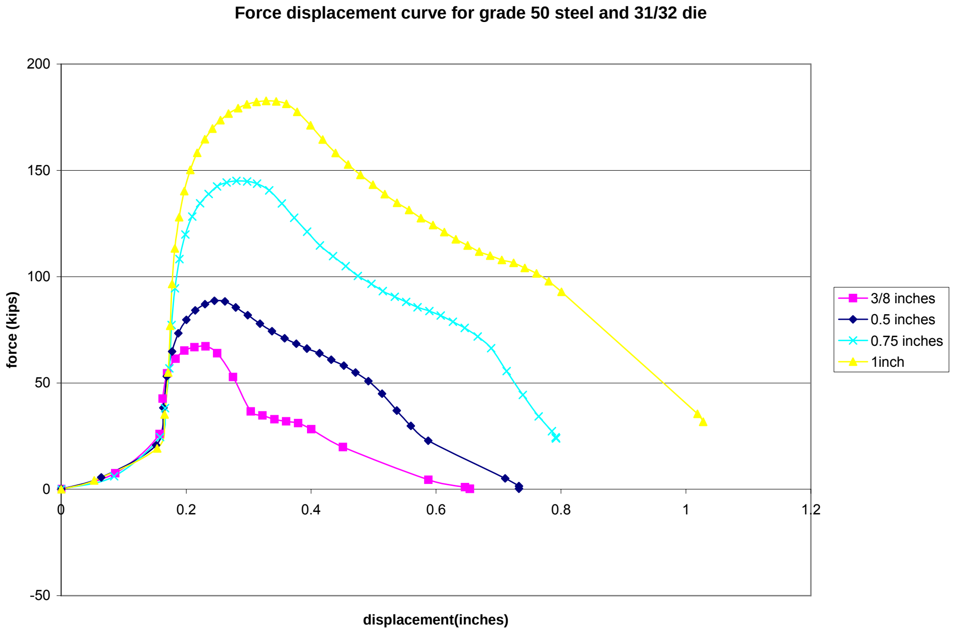


Figure 3-8 Grade 50 steel, 1/32" die clearance

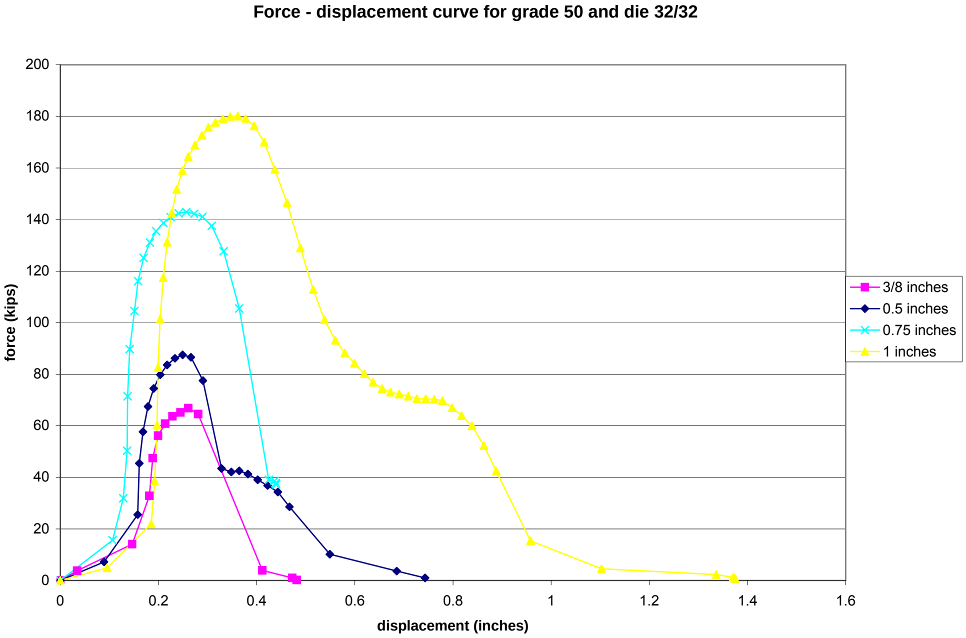


Figure 3-9 Grade 50 steel, 1/16" die clearance

Figure 3-10 Punch hole made in 3/8" plate with 1/32" die clearance

Figure 3-11 Punch hole made in 3/8" plate with 1/16" die clearance

The rest of the graphs for the 1/16" die clearance, besides for the 3/8"plate, are similar. The similarity in the graphs is surprising since for the 1" thick plate 1/16" die clearance should produce the graph of insufficient clearance and it produces graph that is a textbook example of proper clearance.

It should to be noted that the area underneath the curves for 1/16” die clearance is less that the area underneath 1/32” due to the larger clearance and as a result less energy is required for punching a hole.

Figure 3-12 contains only three graphs because tests on 3/8” thick plate with 3/32” die clearance were not made due to risk of damaging the punch.

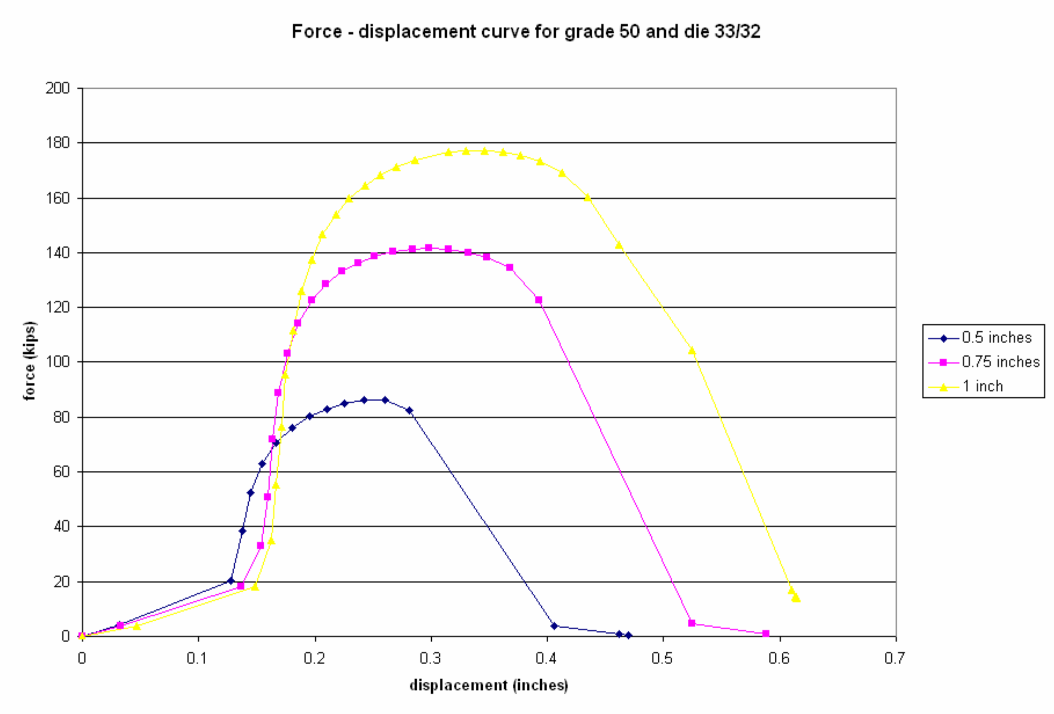


Figure 3-12 Grade 50 steel, 3/32” die clearance

The shapes of the graphs are similar. There is significant and rapid drop in load after maximum load. Also for the three thicknesses the same loud breaking sound was observed as the punch went through the plate indicating that the clearance was too large. Another feature of the graph is that the curves look relatively symmetrical. As was previously observed, the excessive clearance produced relatively smooth hole surfaces when compared to holes with the “proper” clearance as shown in Figure 3-13 . In addition, the excessive also resulted in a larger hole at the bottom of the plate compared with the hole made with smaller die clearance. The hole size at the exit side of the plate matched the die diameter.

The W.A.Whitney's manual suggests that the "perfect" hole will be made when there is no secondary shear and no noticeable fracture angle of the hole, a noticeable fracture angle in the hole is a sign of excessive clearance. However, it is almost impossible to create such a hole since the die clearance has a certain increment, which in this case is 1/32". It seems from the graphs and the figures that the perfect die clearance for ½" thick plate will be somewhere between 1/16" and 3/32". Brown (Brown 2006) reports that the strength and fatigue life of a plate is the same no matter what clearance is used to punch the holes.

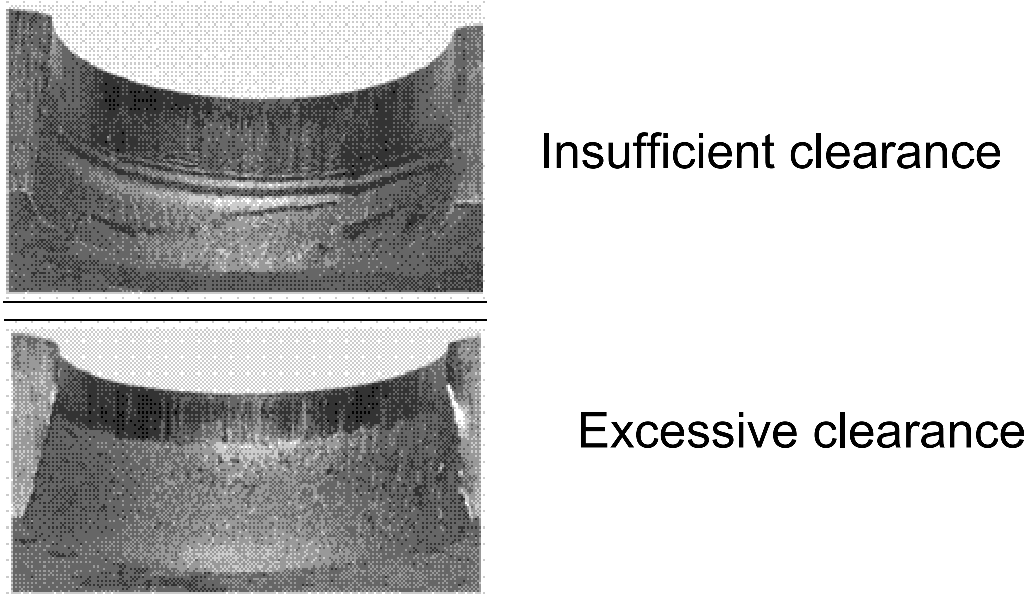


Figure 3-13 1/32" Die clearance vs. 3/32 die clearance

3.4.3.2 Same thickness – different die clearances

The die clearance is the parameter that influences the look of the surface of the hole. The maximum force for the smallest clearance was slightly higher but the difference is 2.5 kips which is less than 3%. As was mentioned before, inadequate clearance produces a rough surface due to the secondary shear, and too much clearance produces a burr and spreading of the bottom portion of the hole. When the hole is made with insufficient clearance more energy is required to punch the hole, which can be important for mechanical press. Excessive clearance creates breakthrough shock and reduces the punch life. However the die clearance is not a factor in terms of the maximum force as evident in Figure 3-14.

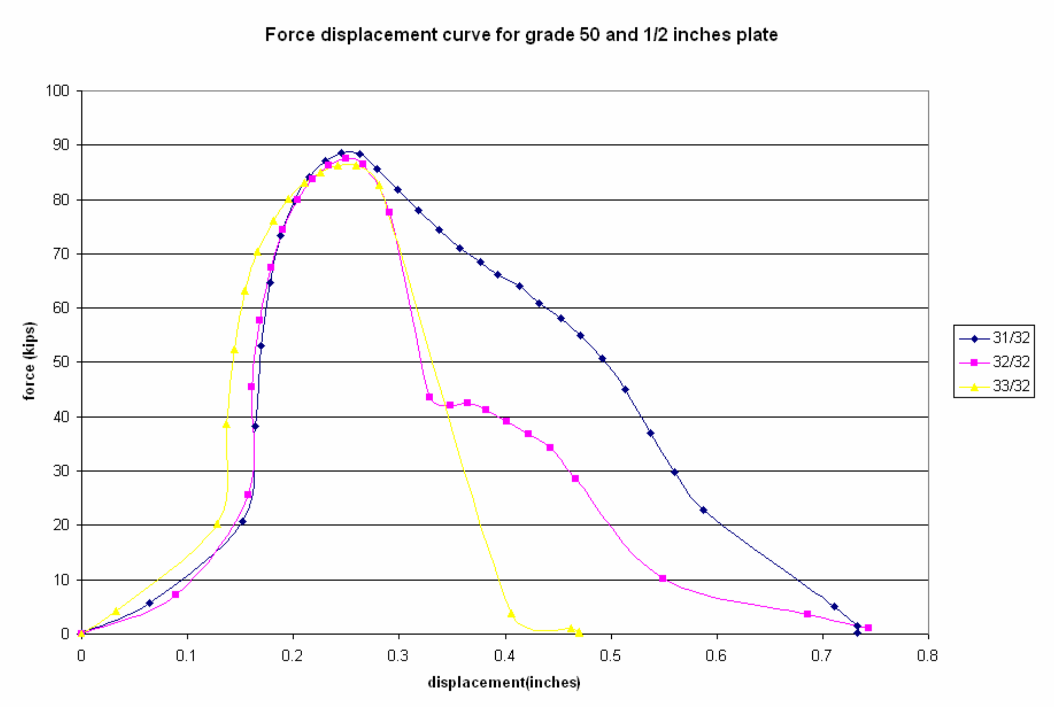


Figure 3-14 Grade 50 steel, ½" plate thickness

CHAPTER 4

Specimen Fabrication and Test Procedure

This work is continuation of the investigations made by Lubitz (2005) and Brown (2006) in Ferguson Laboratory as part of the same research project. They made ultimate and fatigue strength tests of plates with conventional (round) holes and ultimate and fatigue strength of connections. The work presented in the last phase of the investigation focuses on the ultimate and fatigue strength of plates with slotted holes. Cyclic test on galvanized plates and 1” thick plates with 11/16” hole diameter also were to complete the work done in the previous research.

4.1 PLATE TENSION TESTS

The investigation done by Lubitz (2005) and Brown (2006) studied the influence of the parameters listed below:

- Steel type and testing temperature
- Plate thickness and hole size
- Edge distance and edge fabrication method
- Punched hole and die clearance amounts
- Sub-punched and reamed holes.

Only the steel type and the plate thickness were found to have a significant influence on the ultimate strength and ductility of the specimens. For that reason only these two variables and combinations of slotted hole making techniques were included in the research. The slotted holes making techniques studied are:

- 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 4-1 and Figure 4-2 show the stages of fabrication of a slotted hole with both ends punched and oxy act cut between them.

Figure 4-1 Phase 1 of making slotted holes

Figure 4-2 Phase 2 of making of slotted holes

In addition short slotted holes specimens were made and for reference drilled round holes specimens. Figure 4-3, Figure 4-4 and Figure 4-5 show the geometry of the specimens.

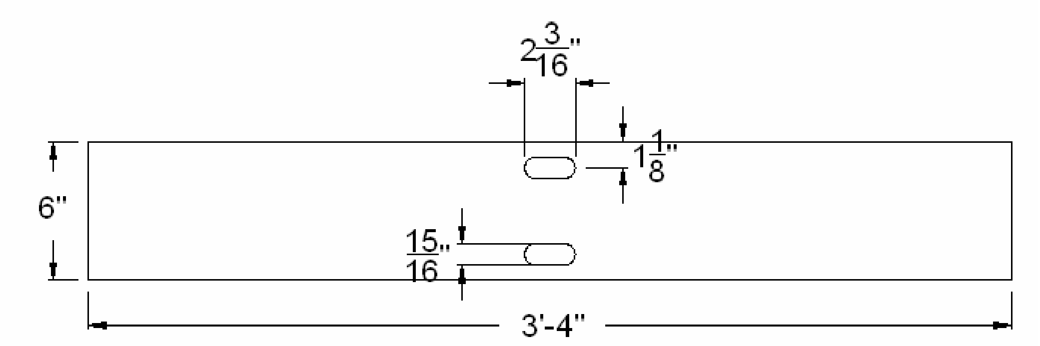


Figure 4-3Long slotted holes specimen

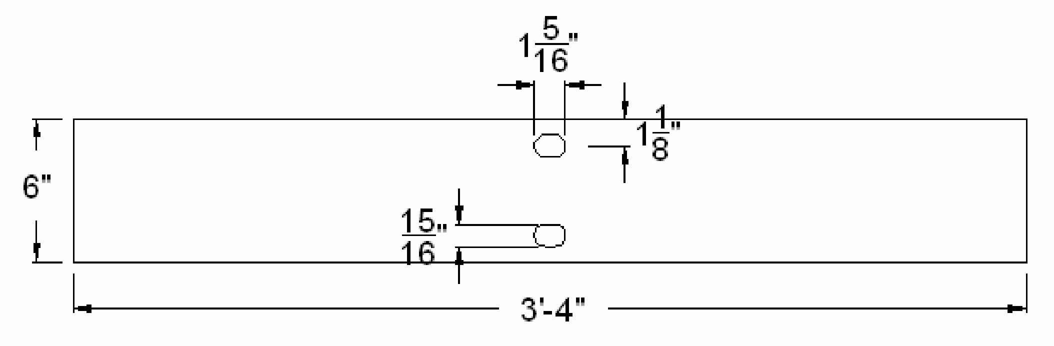


Figure 4-4 Short slotted holes specimen

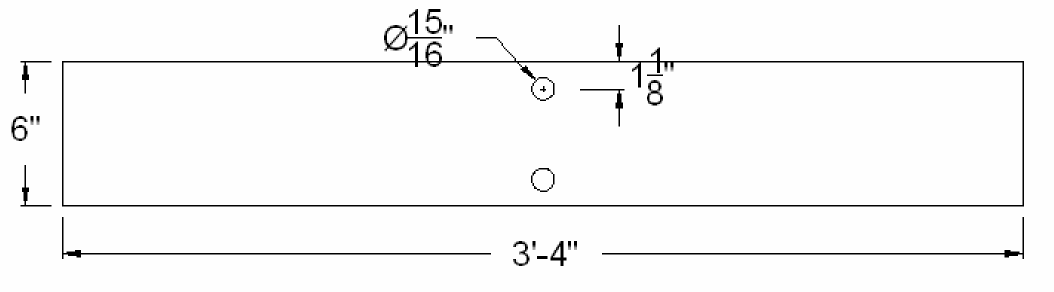


Figure 4-5 Conventional holes specimen

In addition to the specimens prepared in Ferguson Laboratory, 9 specimens were prepared by a fabricator to make a comparison between the techniques used in Ferguson Laboratory and the bridge fabricator. Duplicate test for all available techniques were performed. The test matrices of the specimens that were made in Ferguson lab are shown in Table 4-1, Table 4-2 and Table 4-3. The test matrix for the fabricators specimens is shown in Table 4-4.

Table 4-1 Test matrix A36 steel

	Holes type (2 specimens of each)	
Thickness	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 4-2 Test matrix Grade 50 steel 3/8" thickness

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

Total specimens: 18

Table 4-3 Test matrix Grade 50 steel 3/4" thickness

	Holes type (2 specimens of each)	
Thickness	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 4-4 Test Matrix of the specimens made by outside steel shop

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

4.2 PLATE FATIGUE TESTS

Because of the time constrains it was determined only two cyclic tests on plates with slotted holes to be made. The specimens that were tested were made with both ends punched and oxy act thermal cut between the holes. The thickness of the plates that were tested is 3/8”, this thickness was selected because punching is normally done on thinner plates.

Another common application of punched holes is in the traffic signal structures that are often galvanized. There is a concern (Valtinat and Huhn, 2004) about the influence of the galvanizing on the fatigue life of the elements. Six galvanized plates were tested, with 13/16” holes that were either drilled or punched in 3/8” plates. Two different grades of steel A36 and Grade 50 were used. The test matrix is shown on Table 4-5.

Table 4-5 Galvanized plates test matrix

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

As mentioned in Chapter 2 a rule of the thumb for punching, is that, the diameter of the holes should be larger than the thickness of the plate. Brown's (2006) tests showed the reduction in strength when 11/16" diameter holes are punched in 1" thick plate is very similar to the reduction when a larger hole is punched. To clarify the issue two 1" plates with 11/16" punched holes, one with 1/32"die clearance and the other with 3/32"clearance, and a 1" plate with 11/16" drilled holes were subjected to fatigue testing.

4.3 MATERIAL PROPERTIES

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 were also used for testing the plate and connections. The displacement during testing was monitored by an extensometer with an 8 in. gage length section. The loads and strains were recorded using a digital data acquisition system. This data was in turn used to determine the stress-strain relationship for each type of steel. The data is reported in Table 4-6 along with the mill test reports.

Table 4-6 Material properties

Heat Description	Yield Strength (ksi)	Ultimate Strength (ksi)	% Elong.	f_y/f_u
3/4" Gr. 36	**41.5**	**67.1**	**30**	**0.618**
	40.6	65.0	44	0.624
3/8" Gr. 50	**61.6**	**82**	**22**	**0.75**
	62	80	na	0.775
3/4" Gr. 50	**57.28**	**83.2**	**24**	**0.688**
	54.62	80.62	33	0.677

*Tensile tests made in Ferguson Laboratory – in bold

It is not clear why the measured values do not agree well with the data from the mill report. It is possible that the mill reports were for a different steel heat. The strengths that are used in the discussion are from the Ferguson Laboratory test results.

In addition the chemical composition was of each heat was determined. The results are presented in Table 4-7.

Table 4-7 Chemical composition of steel

Heat Description	C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)
3/4" Gr. 36	0.14	0.73	0.01	0.029	0.15	0.08	0.16	0.04	0.22
3/8" Gr. 50	0.13	0.99	0.011	0.024	0.38	0.06	0.44	0.02	0.37
3/4" Gr. 50	0.19	1.39	0.015	0.009	0.34	0.05	0.05	0.01	0.12

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

4.4 SPECIMEN FABRICATION METHODS

The plates were flame cut to 6 in. wide strips by a steel supplier prior to delivery to the Ferguson Laboratory. The A36 steel was delivered in 20 ft. long sections, and Grade 50 in 10 ft long strips The materials used for the connection tests were also prepared in a similar manner, all the plates were saw cut to the appropriate length.

4.4.1 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 4-6. The image shown in Figure 4-6 Magnetic drill press is courtesy of www.milwaukeetool.com. This drill press was used for all drilled hole sizes, 11/16”, 13/16”, and 15/16” 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 4-6 Magnetic drill press

4.4.2 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 FSEL Punch Press is shown in Figure 4-7.

New punches and dies were used for the project. Figure 4-8 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. A special short slotted punch and die were used for the short slotted holes.

Figure 4-7 Ferguson laboratory punch press

Figure 4-8 Punch and die

4.4.3 Oxy act holes and Plasma cut holes

Oxy act torch and plasma cut were used for making the long slotted holes. In addition to the exclusive torch cutting of holes, the torches were also used in combination with punching or drilling or alone. As seen in Figure 4-9, the oxy act holes were very rough. The precision of the holes, in terms of diameter and position, depend on the skill of the operator. The same can be said about the plasma cut holes too. A typical plasma cut hole is shown in Figure 4-10.

Figure 4-9 Typical full size oxy act slotted hole

Figure 4-10 Typical plasma cut hole

4.4.4 Laser Cut holes

Laser cut holes were done by the fabricator. So far this is not a common hole making technique because of the availability of lasers. Laser cut holes are very smooth and their dimensions are precise and are not dependant on the skills of the operator. A laser cut slotted hole is shown in Figure 4-11.

Figure 4-11 Typical laser cut hole

4.5 PLATE TESTING PROCEDURE

4.5.1 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 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.

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 4-12. The displacement of the crosshead of the machine was measured using a linear potentiometer at the base of the machine. 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 40 kips/min. A digital data acquisition system was used to record the load from the UTM and the displacement readings from the Linear Potentiometer. 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 4-12 Test setup

4.5.2 Fatigue tests

The fatigue tests of the plate specimens were performed using the 220-kip MTS Systems Corp. load frame shown in Figure 4-13. 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.

Each of the plate specimens was tested at a tensile stress range of 25 ksi on the net section so that the maximum load was well below the net section yield stress of the material. The minimum stress was kept at 3 ksi in tension. The corresponding load range was computed using the as-fabricated dimensions. The 3/8” galvanized specimens and slotted holes were tested at 4 Hz frequency and the 1” plates were tested at 3 Hz.


Figure 4-13 Cyclic tests set up

CHAPTER 5

Test Results and Analysis

5.1 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 with the dimensions specified in Figure 4-3, Figure 4-4 and Figure 4-5. The ultimate stress 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, listed in Table 4-6. 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.

5.1.1 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. Table 5-1, Table 5-2 and Table 5-3 show the results from the tests of A36 steel, 3/8” Grade 50 and ¾” Grade 50 steel.

Table 5-1 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 5-2 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 5-3 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.

5.1.2 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. Table 5-4, Table 5-5 and Table 5-6 show the results from the tests of A36 steel, 3/8” Grade 50 and ¾” Grade 50 steel.

Table 5-4 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 5-5 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 5-6 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.

5.1.3 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. Table 5-7, Table 5-8 and Table 5-9 show the results from the tests of A36 steel, 3/8” Grade 50 and ¾” Grade 50 steel.

Table 5-7 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 5-8 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 5-9 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.

5.1.4 Punched holes

Results presented in this section are focusing on the influence of punching full size short and long slotted holes. Table 5-10, Table 5-11 and Table 5-12 show the results from the tests of A36 steel, 3/8” Grade 50 and ¾” Grade 50 steel.

Table 5-10 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 5-11 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 5-12 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.

5.1.5 Summary and analysis

As was described in Chapter 4 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 3 drilled – plasma specimens, 1 fabricators long slotted specimen, 1 laser cut specimen,3 oxy full size specimens and 2 plasma full size specimens went from over 1 strength ratio to less than 1. All the recalculated values are presented in appendix B. As expected the majority of the specimens that reduced to less than 1 when using nominal hole size were those that were made by using 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 5-1.

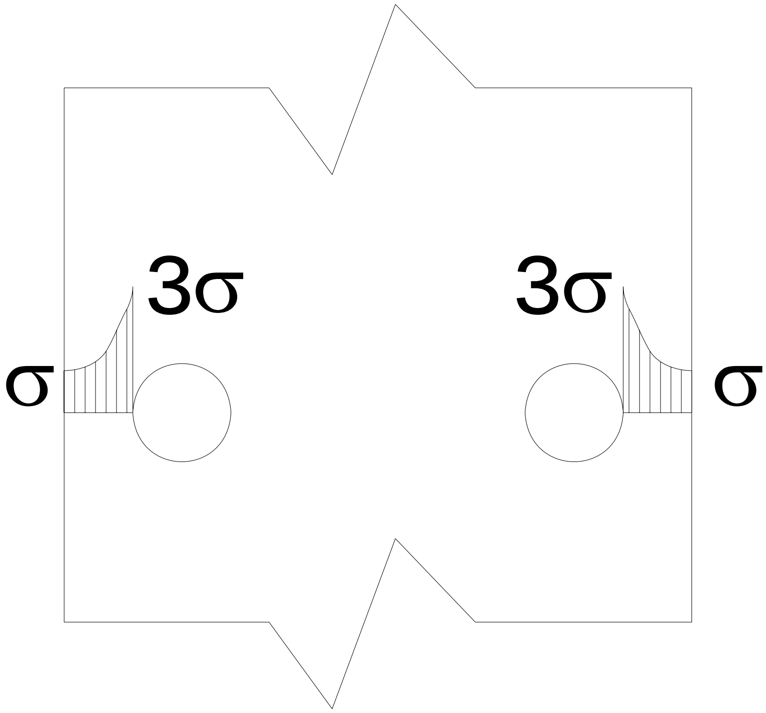


Figure 5-1 Distribution of stresses around round holes

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 coupon test. 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 5-2 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.

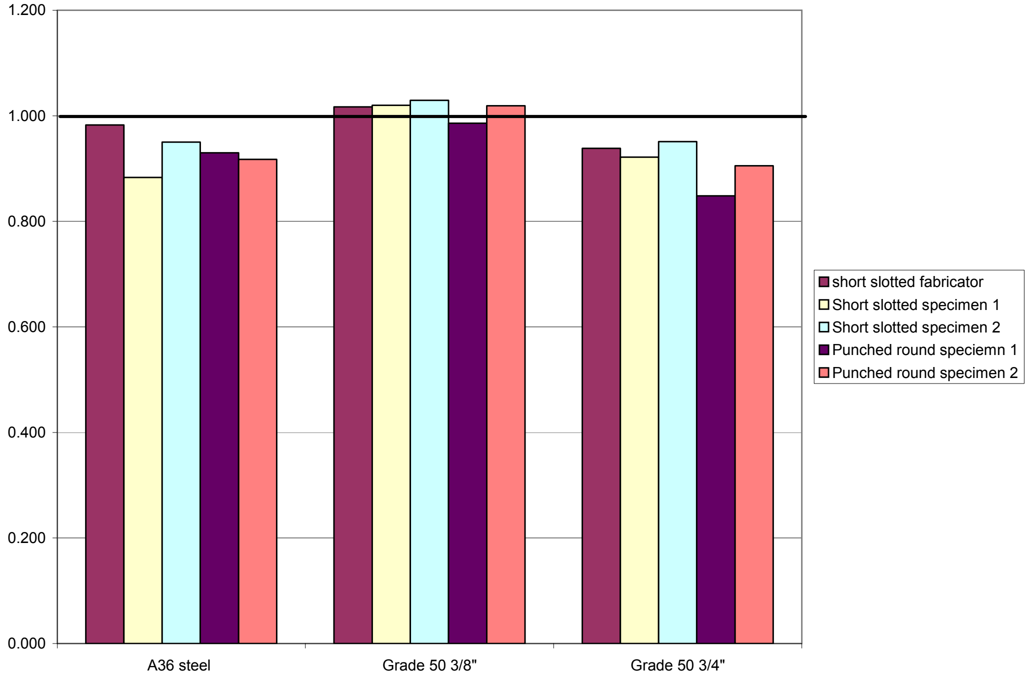


Figure 5-2 Strength ratio of short slotted and punched round holes

Figure 5-3 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.

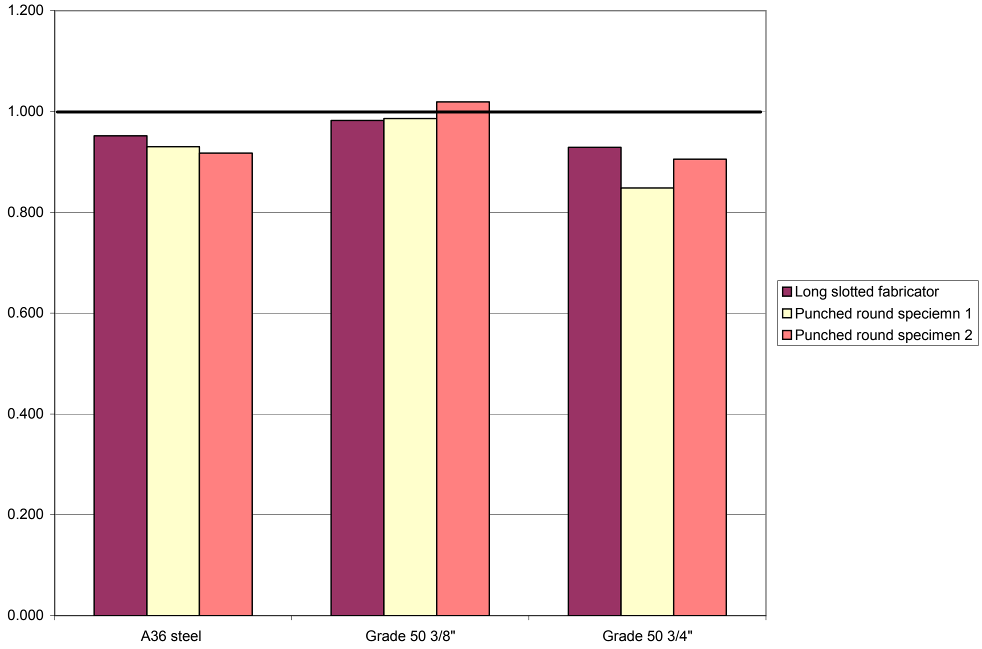


Figure 5-3 Long slotted punched holes vs. Punched round holes

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.

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 5-4.shows a typical tensile failure of a specimen with two slotted holes.

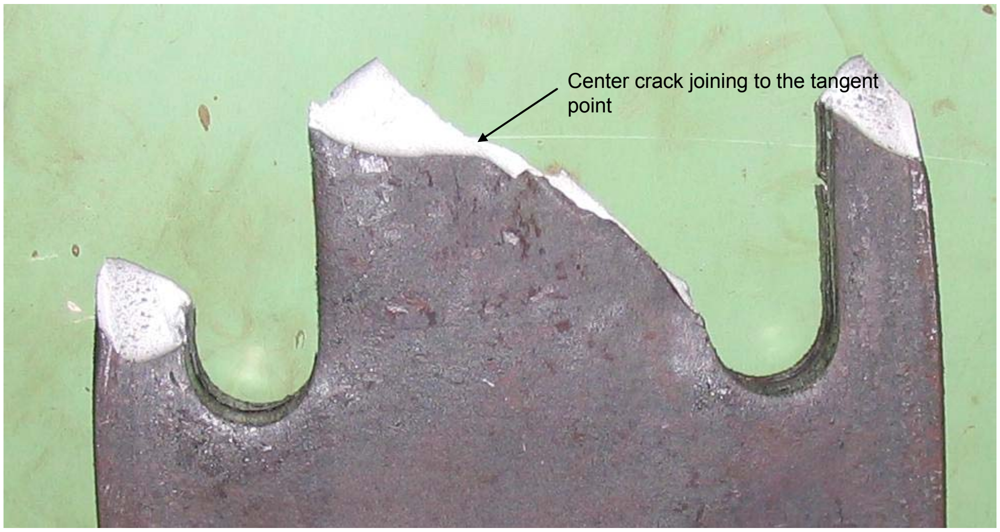


Figure 5-4 Typical failure mode of long slotted punched holes

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 5-5.

Figure 5-5 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 5-6 shows the fractures of the two replicate specimens.

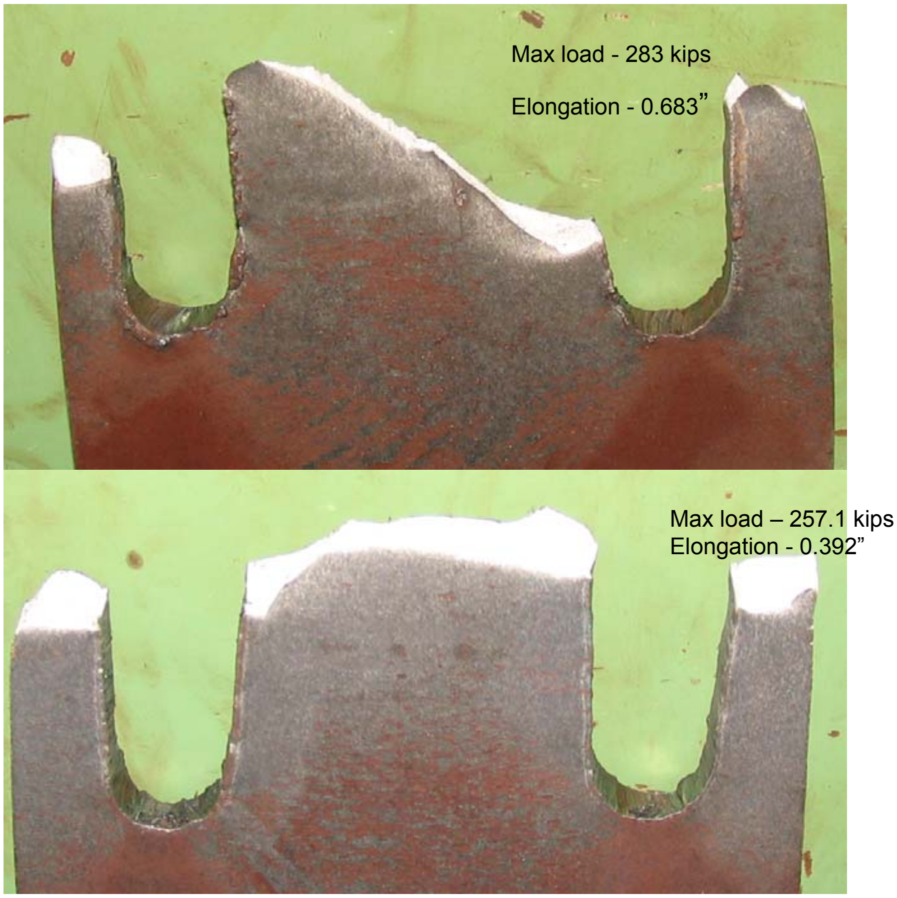


Figure 5-6 Grade 50 3/8” Specimens 1 and 2

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 5-7.

Figure 5-7 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 5-8. The other failed specimens are shown in Appendix C. 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 5-9 and in Figure 5-10. In Figure 5-11, however, 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 5-8Brittle fracture of punched plasma Grade 50 ¾” plate

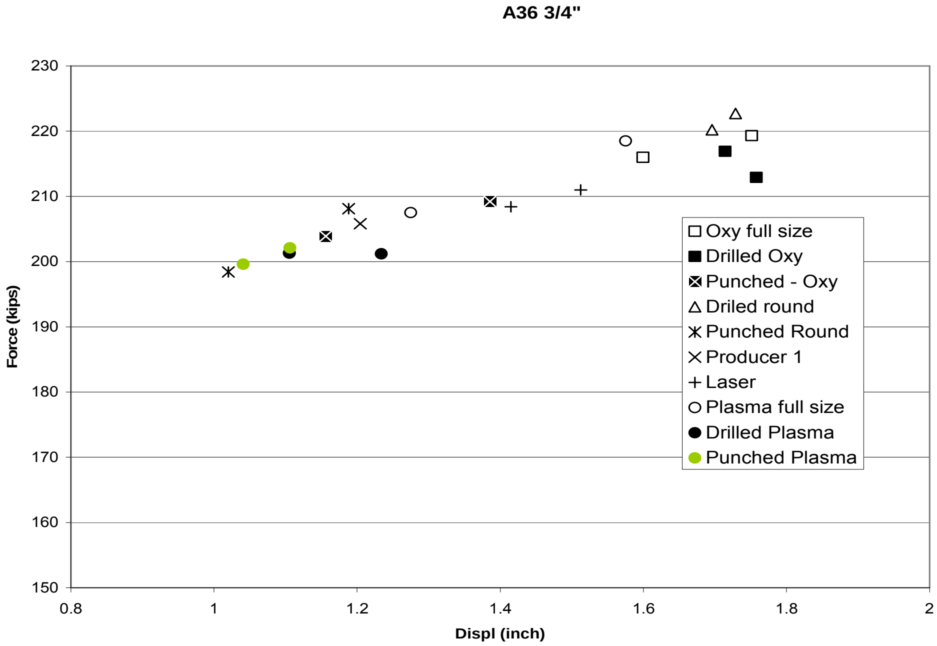


Figure 5-9 A36 Steel ¾" thick plate

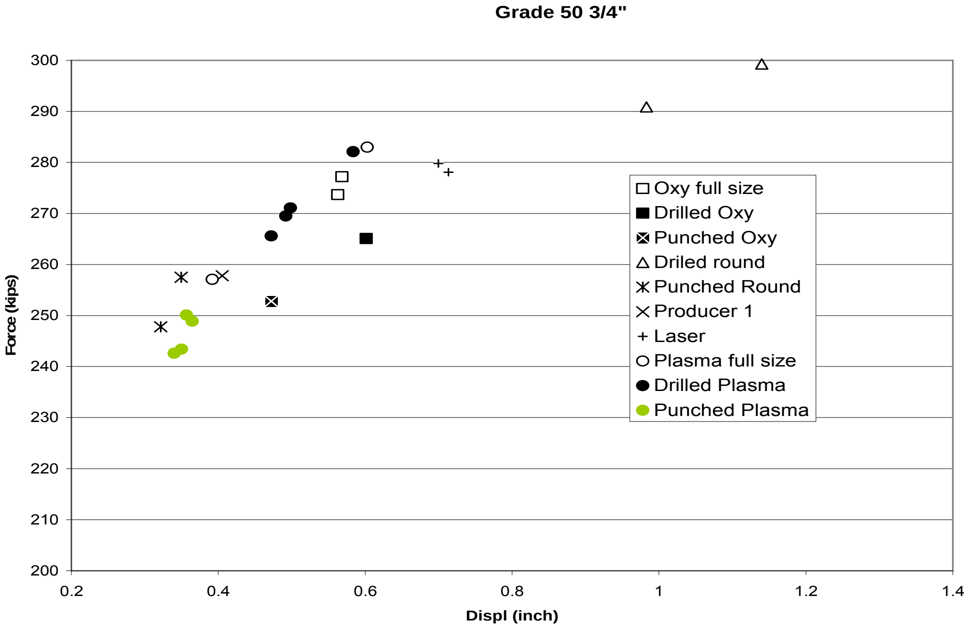


Figure 5-10 Grade 50 Steel ¾" thick plate

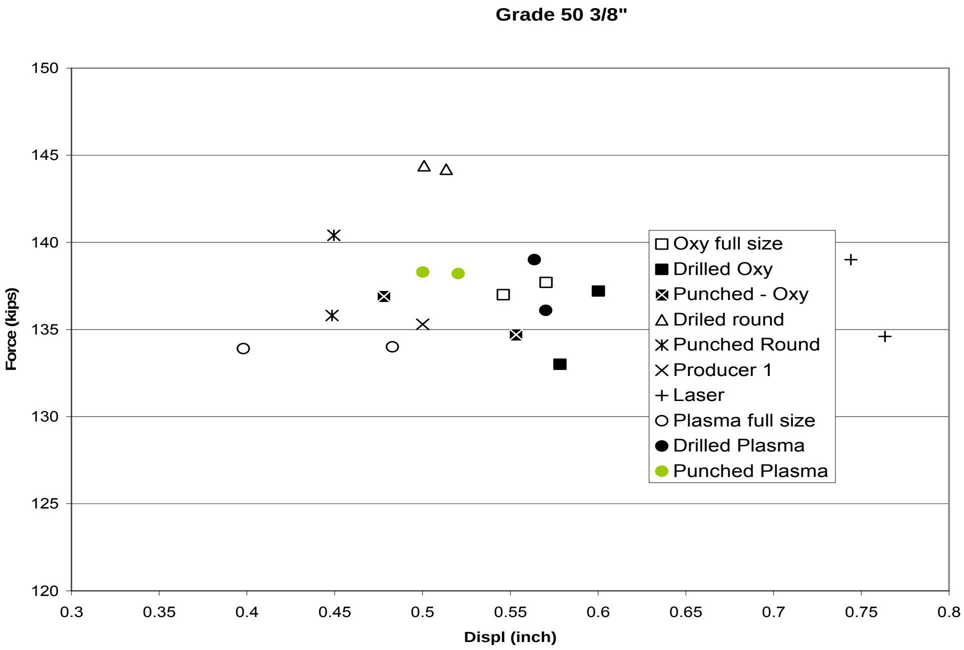


Figure 5-11 Grade 50 Steel 3/8" thick plate

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, like the Producer 1 ones, have strengths equal to and to 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

5.2 FATIGUE TESTS RESULTS

5.2.1 Galvanizing Investigation

The geometry of the galvanized specimens were shown in Figure 4-5. Their plate thickness was 3/8”. The results of the fatigue tests are shown in Table 5-13 and are compared with results from tests of non galvanized ½” thick specimens with the same geometry reported by Brown (2006).

Table 5-13 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	Na*	777,653
	Punched 1	170,678	662,744
	Punched 2	122,637	na

* - galvanized drilled A36 specimen failed in tension 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." Although the same trends were observed in the Ferguson Laboratory tests, a sharper reduction ratio was onserved of more than 3.0.

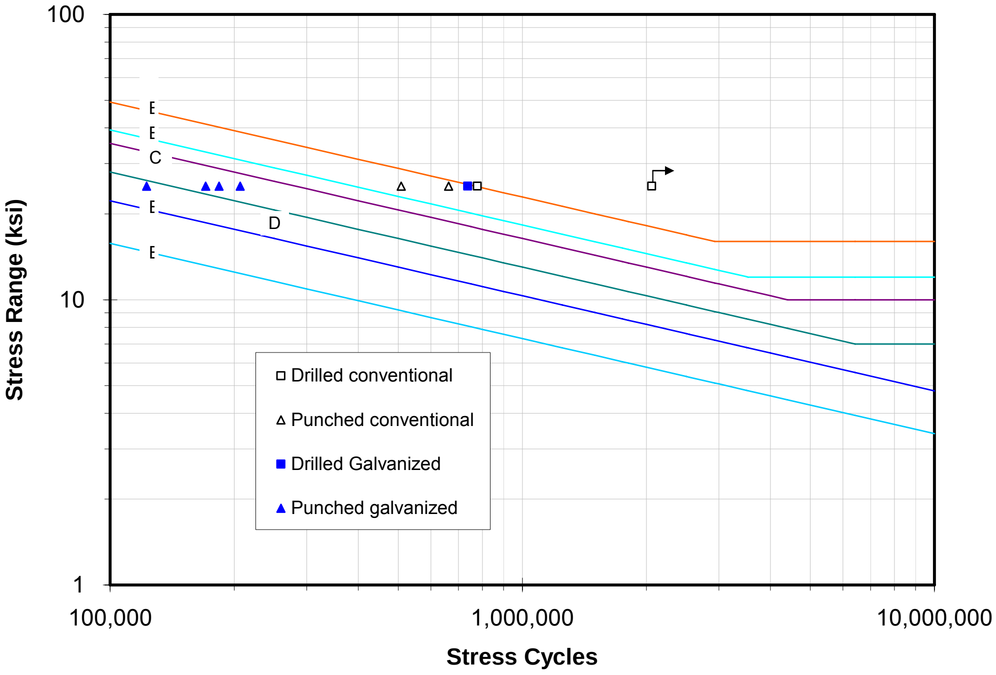


Figure 5-12 Galvanized Specimens

From Figure 5-12 can be seen that the reduction due to the galvanizing moves the drilled specimens is from category B to B'. For the punched specimens the reduction due to galvanizing is much more significant. The fatigue lives of the galvanized punched specimens are reduced from category B' to category E'.

5.2.2 Slotted holes investigation

Two punched – oxy act holes specimens were tested in fatigue. The results are shown in Table 5-14 and are compared with 13/16” holes, ½” thick plate specimens.

Table 5-14 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 hole specimens are superior to the slotted holes. The lower endurance of the slotted holes probably is due to the double “torture” of the material around the hole. First, punching creates microcracks around the holes and after this the same area is burned by the oxy act torch, and as a result the cracks size gets bigger and leads to lower fatigue life. However, the reduction is not that significant as was observed in the galvanized specimen as can be seen in Figure 5-13. The detail category drops from B' for punched holes to C for slotted holes.

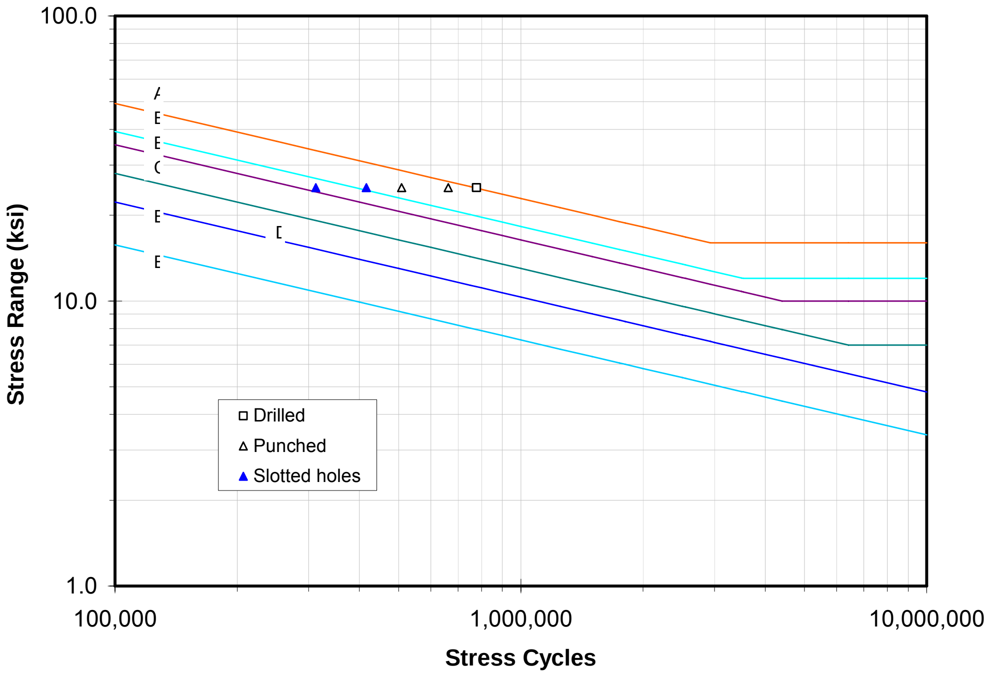


Figure 5-13 Slotted holes specimens results

5.2.3 One inch thick plates investigation

Three one inch thick plates were fatigue tested - 1 drilled and 2 punched holes specimens. The diameter of the holes was 11/16" and the two different die clearances, 1/32" and 3/32", were used when punching. The results are compared with the results reported by Brown (2006) from with ½ thick plate specimens with 11/16" diameter holes. The fatigue tests results of the 1 inch plates are shown in Table 5-15.

Table 5-15 Thick plate investigation

Specimen	Fatigue life (cycles)
Drilled A36 1/2” plate	768,176
Punched A36 ½” plate	582,286
Punched Gr50 ½”plate	2,059,758**
Drilled 1”plate	759,178
Punched 1”3/32” die clearance	2,100,640**
Punched 1”1/32” die clearance	2,004,129**

** - run out specimens

The results are surprising because in two occasions the punched holes specimens are superior to the drilled ones. The author never found in the literature another investigation that shows the same paradox. Note that fatigue tests were done on specimens that break the “Do not punch a hole with smaller diameter than the thickness of the hole!” rule, and tests on specimens thicker than the diameter of the holes punched in them may not have been done before. The results are surprising. One possible explanation may be due the residual compressive stresses around the hole created by hole punching. For example the specimen that ran out was slightly bulged after punching as shown in Figure 5-14. The bulged material adjacent to the hole would have compressive stresses after punching. Even though the stress range is the same as in the drilled hole, the residual compression may benefit the fatigue life.

Figure 5-14 Example of bulging created hole punching

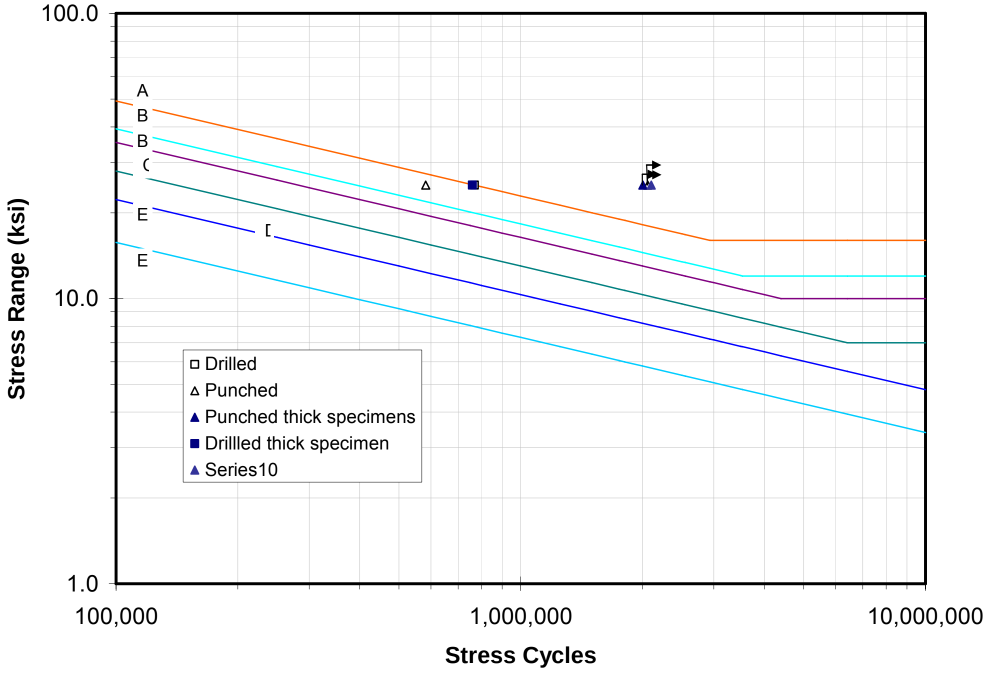


Figure 5-15 Thick specimens results

As can be seen in Figure 5-15 the drilled hole 1 inch specimen lies over the ½” thick plate specimen. However, the punched one is above the category A line.

CHAPTER 6

Conclusions

6.1 PROJECT SUMMARY

Slotted holes are used in the construction of the buildings and bridges to increase the construction tolerances. Sometimes they are specified by the designers but most of the time they are made on the field when the elements to be connected do not fit and the fastener cannot get into both holes. The latter does not happen in main members of bridges since they are normally required to be assembled in the fabrication shop. However, there are no requirements in AASHTO specifications that forbid the use of slotted holes in bridge construction if specified by the designer. Also, there is not a lot of information of behavior of slotted holes under static and fatigue loading. A total of 63 ultimate strength tests and 2 fatigue tests were conducted to investigate the behavior of slotted holes behavior and to compare different slotted holes fabrication techniques.

Results summary:

- slotted holes, made with all the techniques, are in between the punched and drilled in terms strength and elongation
- short slotted and punched full size holes behave similar to punched round 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 ends and oxy or plasma cut between slots joining the round drilled or punched holes

- Laser cut holes were no better than the holes made by other methods even though they had much smoother and uniform surface
- slotted holes made by punched holes at both ends and then oxy act between the holes have less fatigue life than the punched holes

Most of the accessories of the bridges- mast arms, traffic signal posts, are galvanized. However, there is no information about the influence of the galvanizing of the fatigue elements. A total of 5 fatigue tests were completed to investigate the influence of the galvanizing on the endurance of the plates.

Results summary:

- galvanizing significantly reduces the fatigue life of the drilled and punched hole specimens
- galvanizing the drilled hole specimen puts them in the same category as an ungalvanized plate with punched holes specimen

Punching holes in thick members was a problem because of the large force that required for punching. Also, the thick members are not primary candidates for punching because, as said before, it is easier to move the drilling machine and make the holes, than to move large elements to the punch press. The third problem with punching of thick members is "the rule of thumb" that one cannot punch a hole in member that is thicker than the diameter of the hole. However, the 2005 AISC Specifications removed any limitations and acknowledged that previous thickness limitations were controlled by common practice and equipment capabilities. A search of the literature did not show any research that supports or opposes removing this limitation. A total 3 fatigue tests were made to investigate the behavior of plates with punched holes smaller than the plate thickness under cyclic loads.

- punched hole specimens with holes smaller in diameter than the plate thickness have higher fatigue life than the drilled hole specimen and much higher than plates with punched holes larger than the plate thickness

6.2 DESIGN AND CONSTRUCTION SPECIFICATION CONSIDERATIONS

Short and long slotted holes are allowed in both the AISC and AASHTO specifications. Strength equations, resistance factors, and fatigue categories are the same for slotted holes as for the round holes.

Slotted holes should not be allowed in connections that require ductility, as slotted hole displacements from some of the plate tests were 50% lower than replicate drilled hole specimens.

Current AASHTO and AISC Specifications require a 1/16 in. addition to hole diameter in the calculation of the net section, regardless of the hole type. However, Brown (2006) showed that 10 % increase of the hole diameter only for punched holes to account for the lost strength due to punching is a good solution for calculating the net area of a member. No increase of the diameter of the hole is needed for drilled holes. Slotted holes have more strength than punched holes but less than the drilled. A 10 % increase of the shorter dimension when the holes are parallel to the load for the slotted holes provides a reasonable solution.

AASHTO specifications do not explicitly prohibit slotted holes on primary members. The fatigue test results show a reduction in the fatigue life of the long slotted holes made by punching both ends and oxy act cut between them compared with the punched holes. The punched holes used in connections with pretension bolts had the same fatigue life as the drilled holes because of the compression applied of the pretensioned force. This is not the case with long slotted holes because there is no guarantee where the bolt will end up and it cannot press the whole area around the hole, so it does not make sense to allow slotted holes and the prohibit the punched holes in primary members when the latter are superior in fatigue. One solution of this problem is to prohibit slotted holes on the primary members regardless of the hole making technique as with the punched holes. The other is to fund a research which to investigate the fatigue life of every long slotted making technique and to assign a category for every one of them. For example the category for punched – oxy act can be C.

So far there is no assigned category for the galvanized members in both AASHTO and AISC specifications. The elements that are primary candidates to be galvanized, traffic light posts etc, are not considered primary members. However, category C can be assigned for galvanized drilled members and category E can be assigned for galvanized members.

AASHTO LRFD specifications do not allow punched holes in primary members. The current AASHTO Construction 2004 limits the thickness of material that can be punched for different grades of steel based upon equipment limitations and common practice. The common practice is – “do not punch hole in element thicker than the diameter of the hole”. Tests from this study show that the fatigue life of the thick members with holes with diameter less than the thickness of the hole have higher endurance than drilled holes specimens. More research needs to be done to investigate what combination of thickness and hole diameter result in an increase in the fatigue life of the member. However it is clear that the maximum thickness requirement can be removed.

APPENDIX A

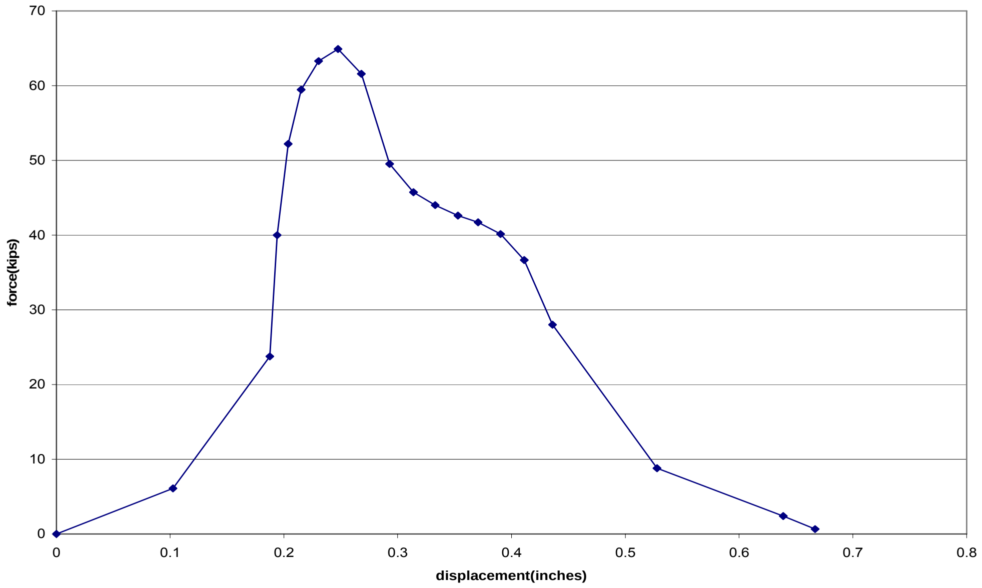


Figure A- 1 Force vs. punch displacement for A36, 3/8” plate, 1/32” die cl.

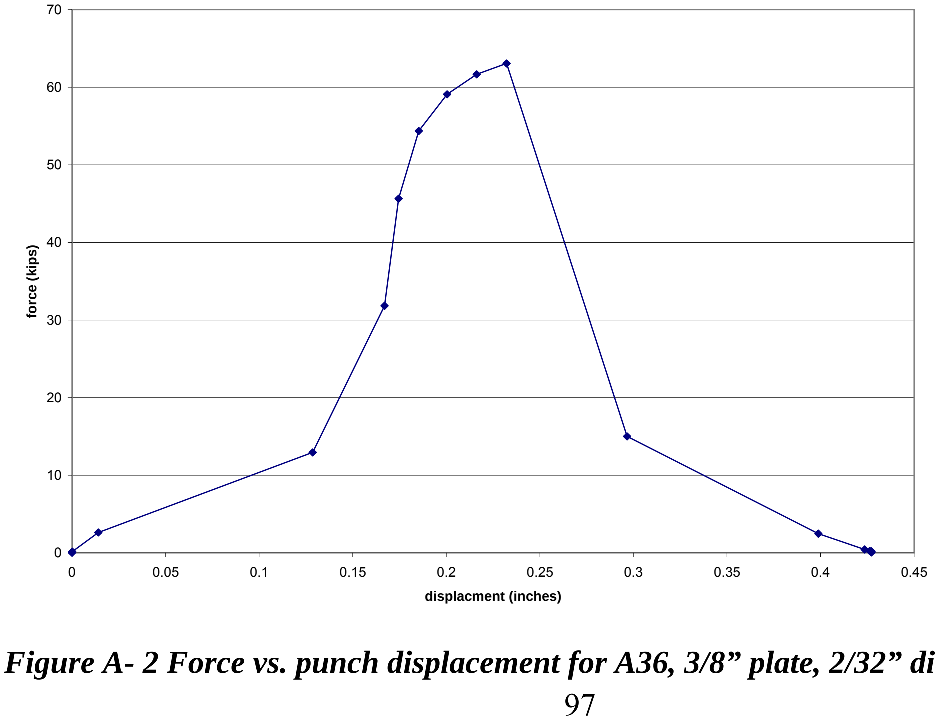


Figure A- 2 Force vs. punch displacement for A36, 3/8” plate, 2/32” die cl.

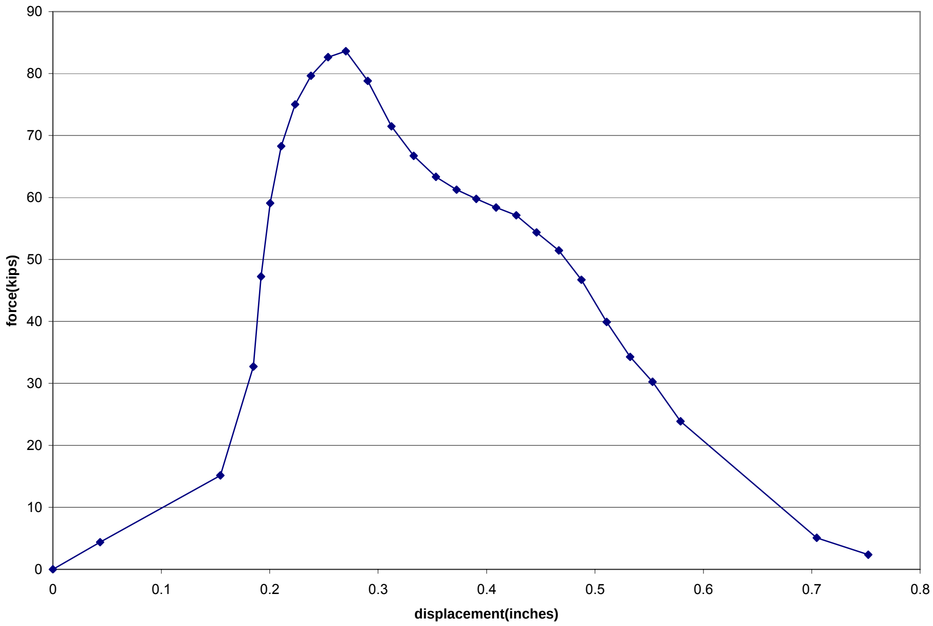


Figure A- 3 Force vs. punch displacement for A36, 1/2” plate, 1/32” die cl.

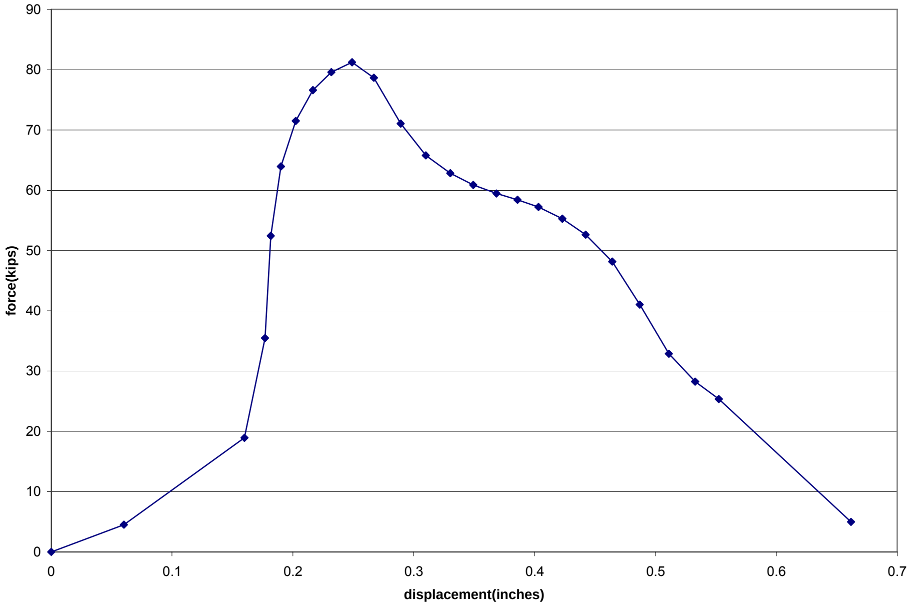


Figure A- 4 Force vs. punch displacement for A36, 1/2”yielded plate, 1/32” die cl.

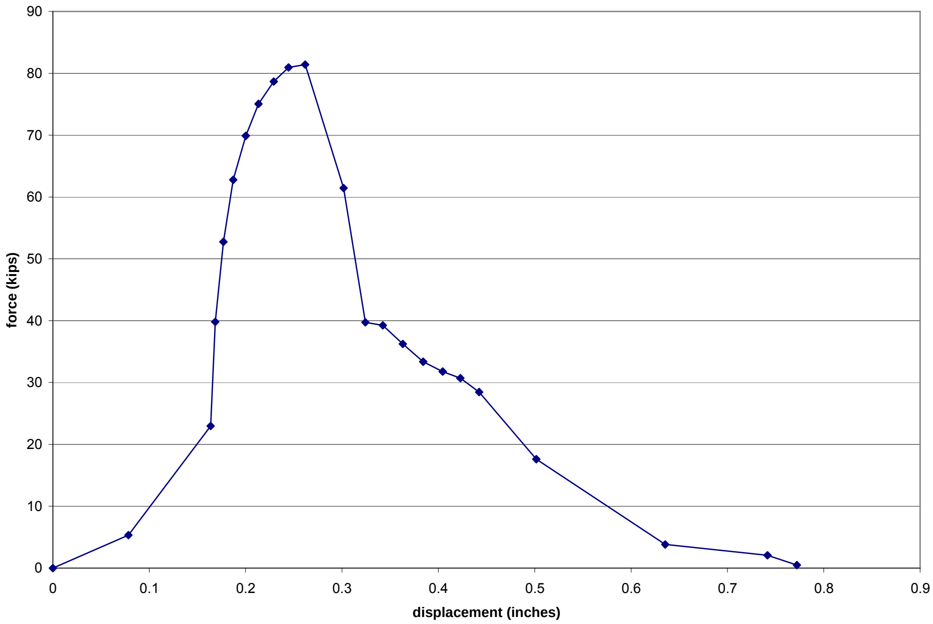


Figure A- 5 Force vs. punch displacement for A36, 1/2” plate, 2/32” die cl.

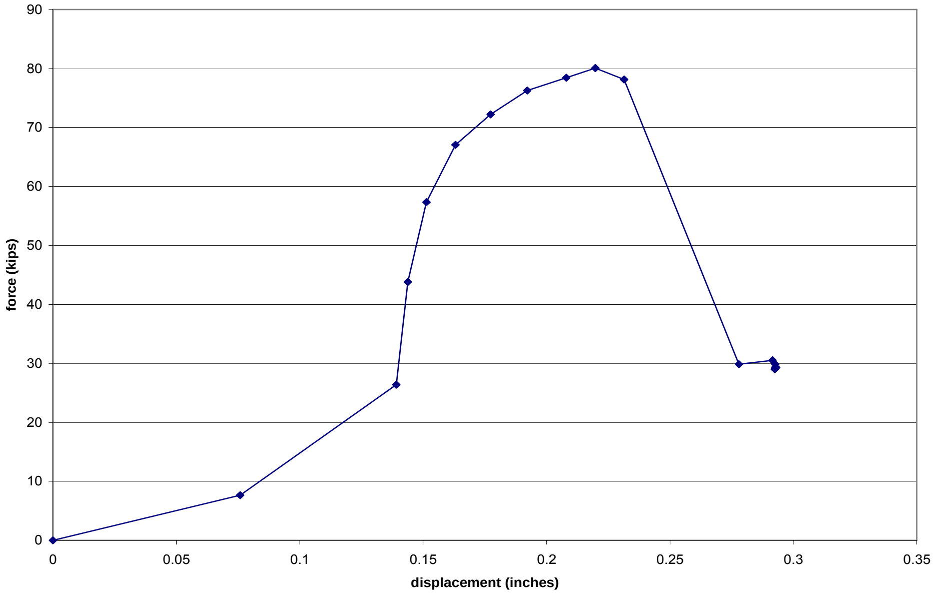


Figure A- 6 Force vs. punch displacement for A36, 1/2”yielded plate, 2/32” die cl.

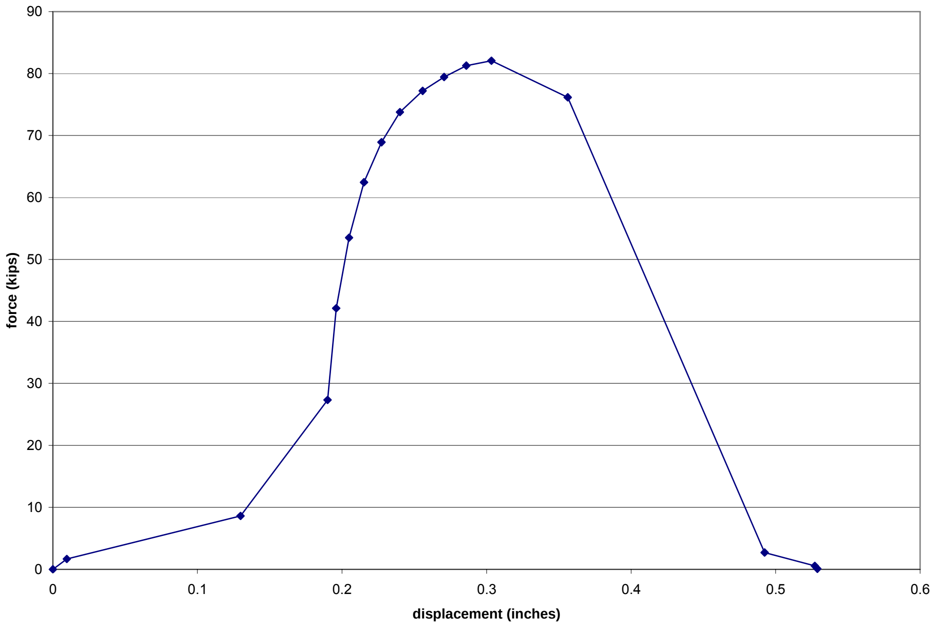


Figure A- 7 Force vs. punch displacement for A36, 1/2” plate, 3/32” die cl.

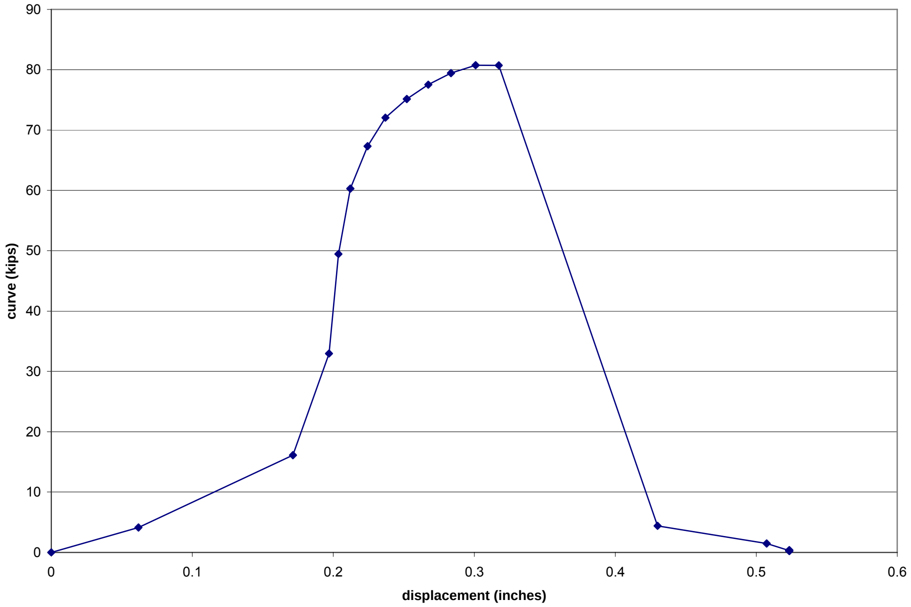


Figure A- 8 Force vs. punch displacement for A36, 1/2”yielded plate, 3/32” die cl.

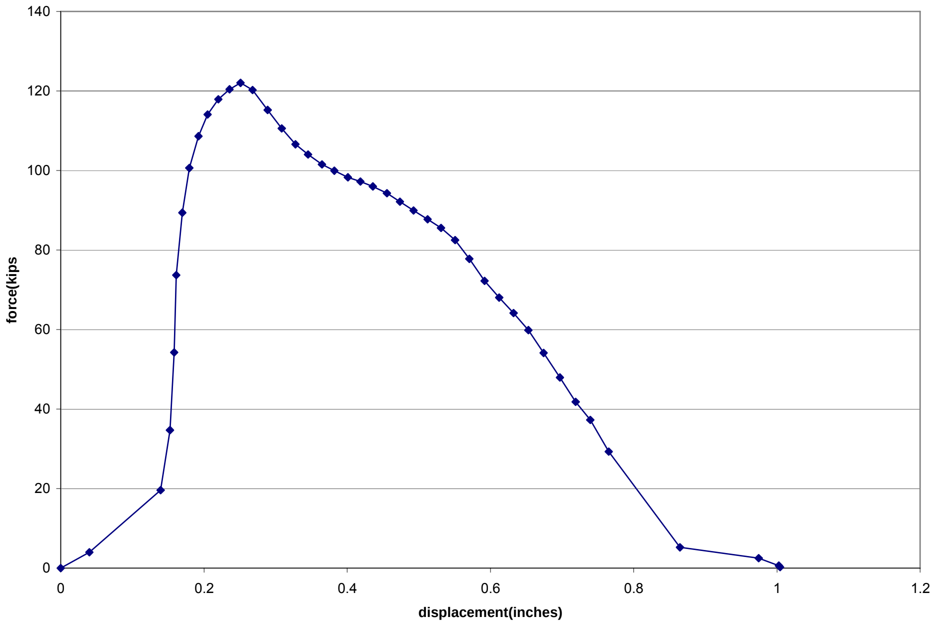


Figure A- 9 Force vs. punch displacement for A36, 3/4” plate, 1/32” die cl.

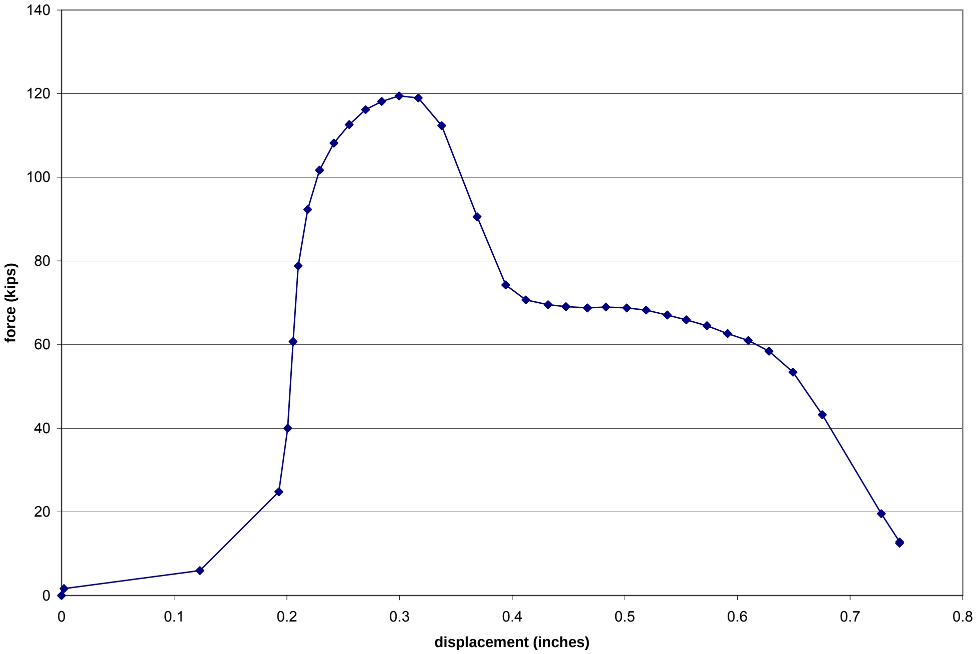


Figure A- 10 Force vs. punch displacement for A36, 3/4” plate, 2/32” die cl.

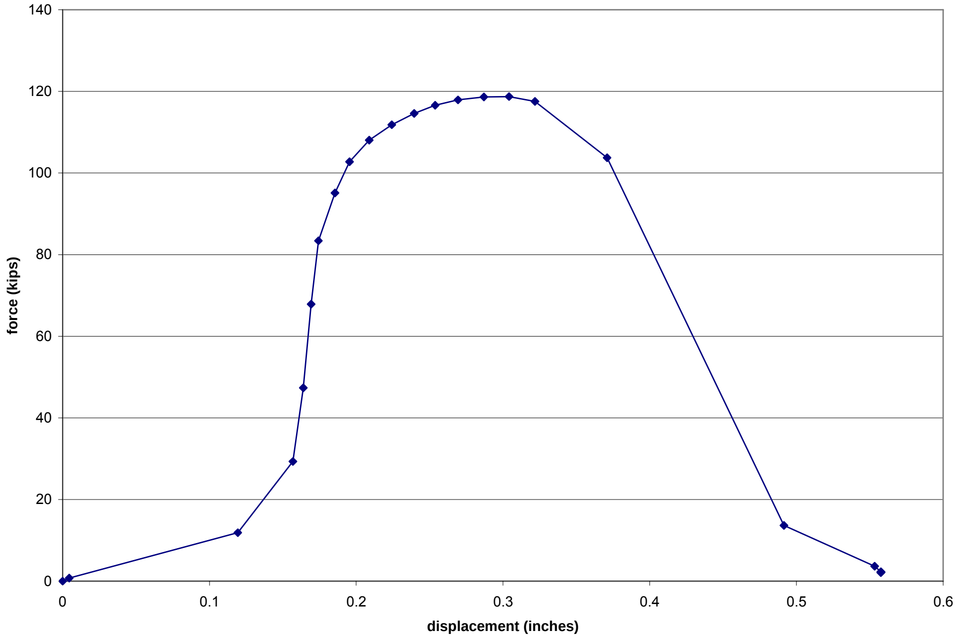


Figure A- 11 Force vs. punch displacement for A36, 3/4" plate, 3/32" die cl.

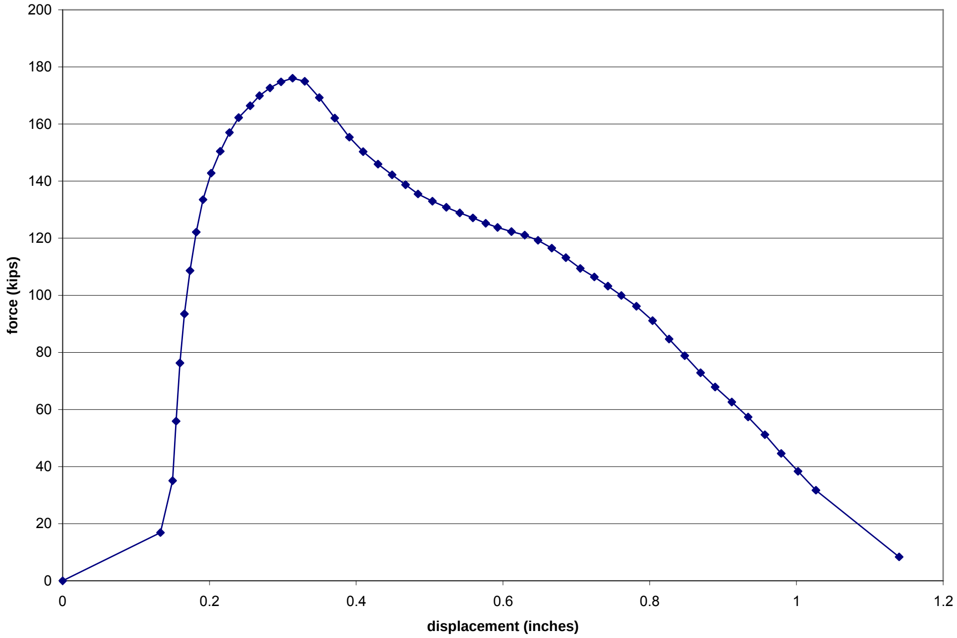


Figure A- 12 Force vs. punch displacement for A36, 1" plate, 1/32" die cl.

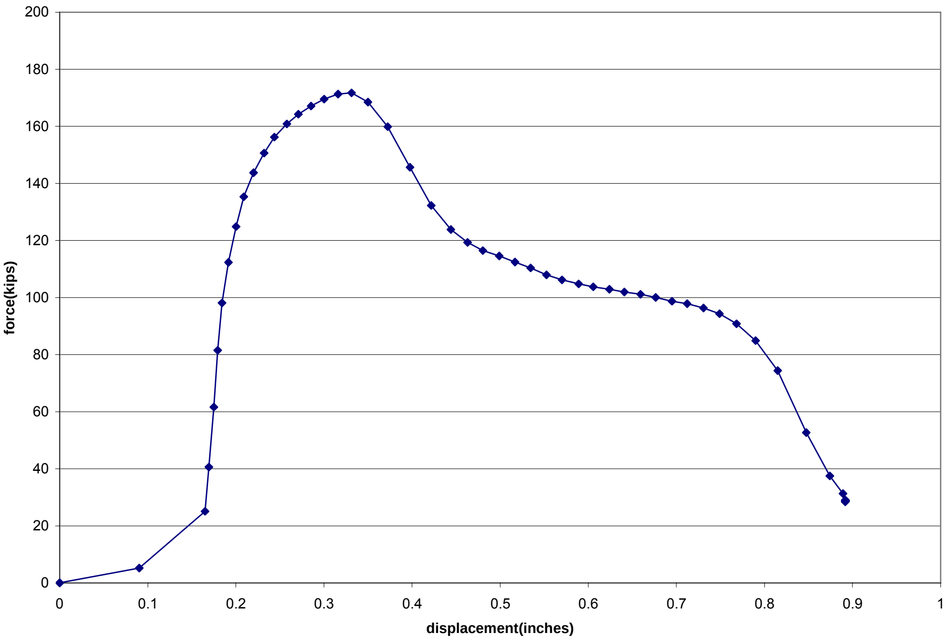


Figure A- 13 Force vs. punch displacement for A36, 1" plate, 2/32" die cl.

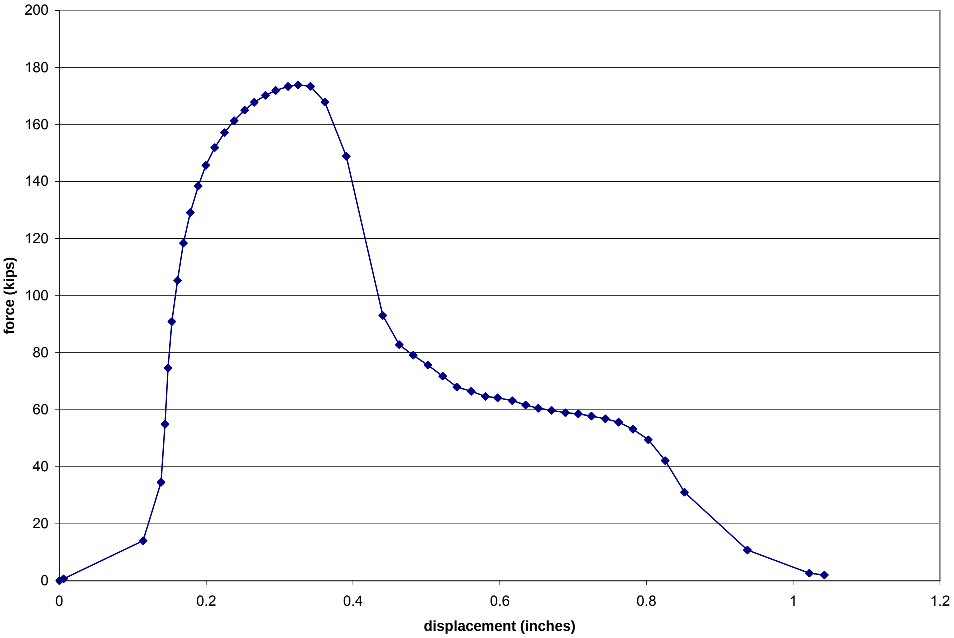


Figure A- 14 Force vs. punch displacement for A36, 1" plate, 2/32" die cl.

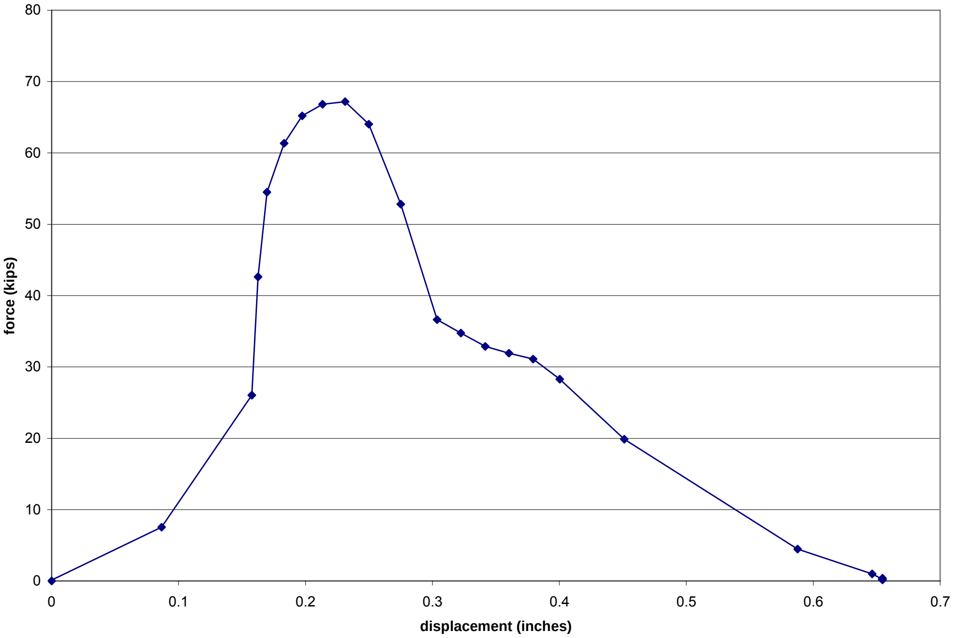


Figure A- 15 Force vs. punch displacement for Gr.50, 3/8” plate, 1/32” die cl.

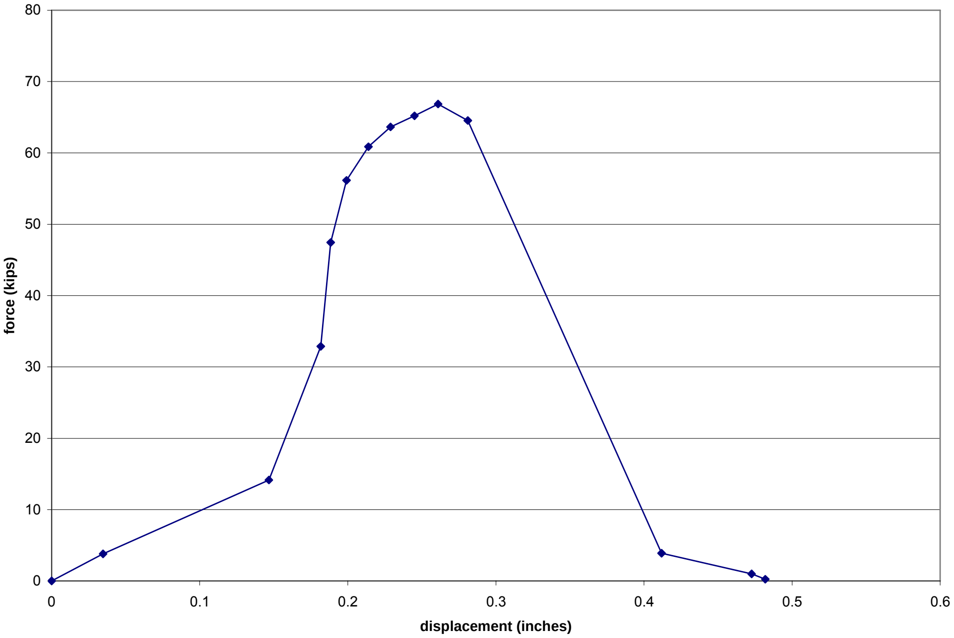


Figure A- 16 Force vs. punch displacement for Gr.50, 3/8” plate, 2/32” die cl.

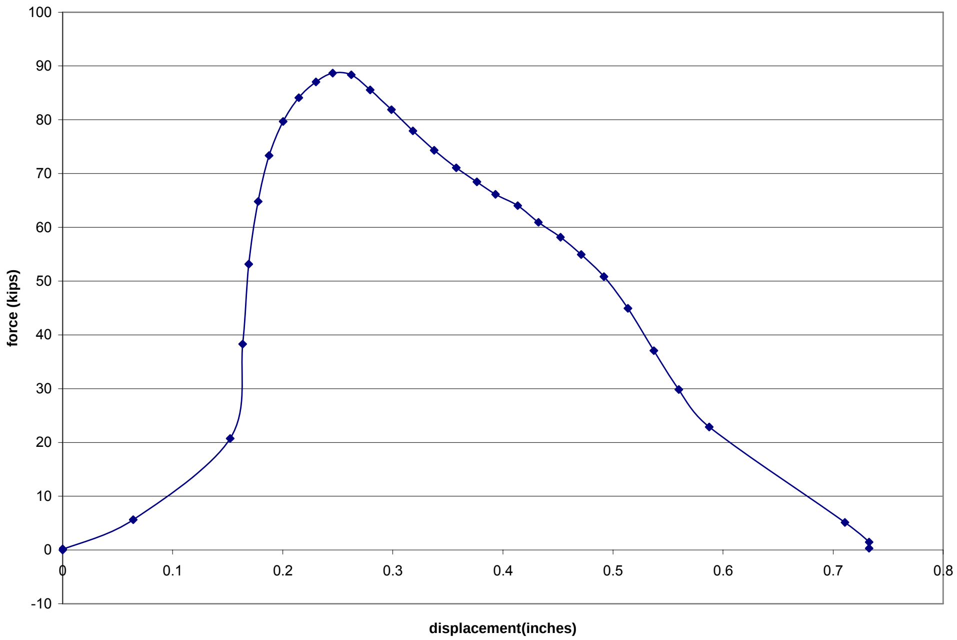


Figure A- 17 Force vs. punch displacement for Gr.50, 1/2" plate, 1/32" die cl.

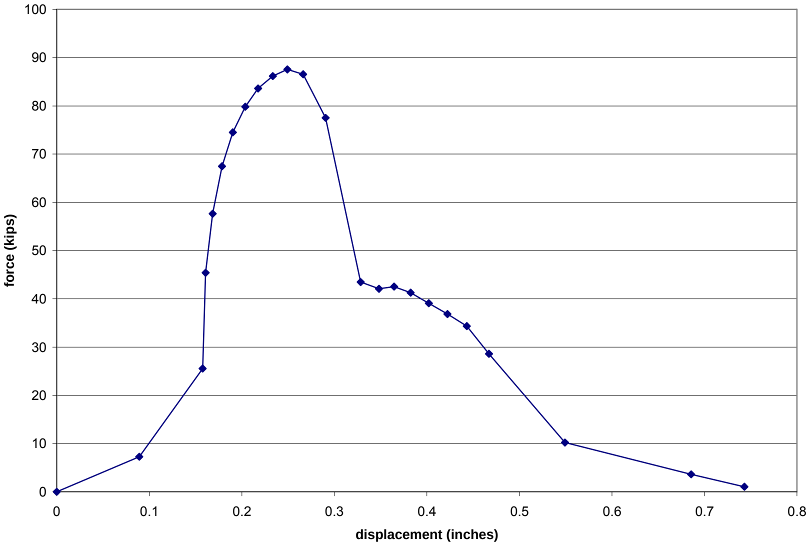


Figure A- 18 Force vs. punch displacement for Gr.50, 1/2" plate, 2/32" die cl.

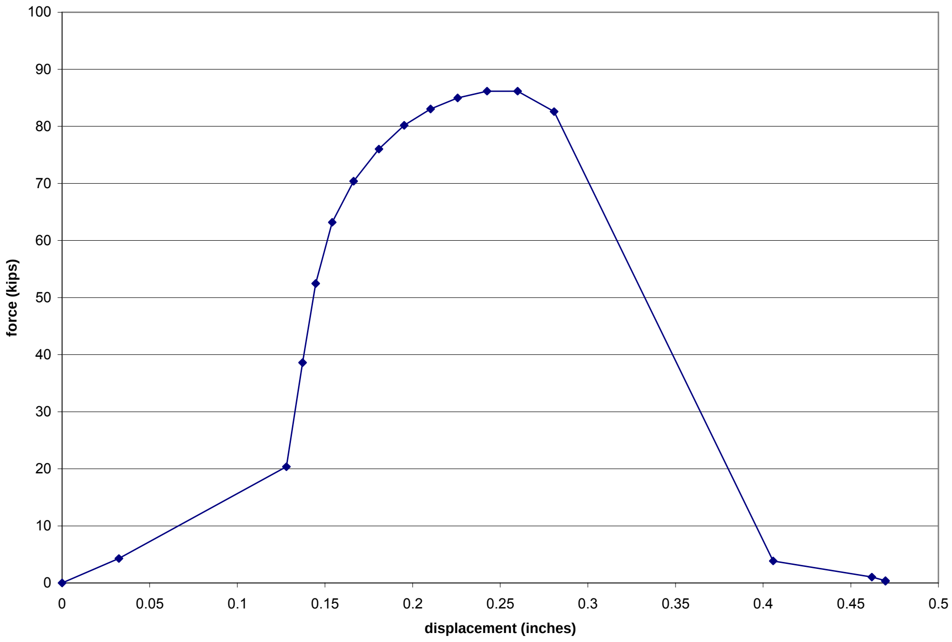


Figure A- 19 Force vs. punch displacement for Gr.50, 1/2" plate, 3/32" die cl.

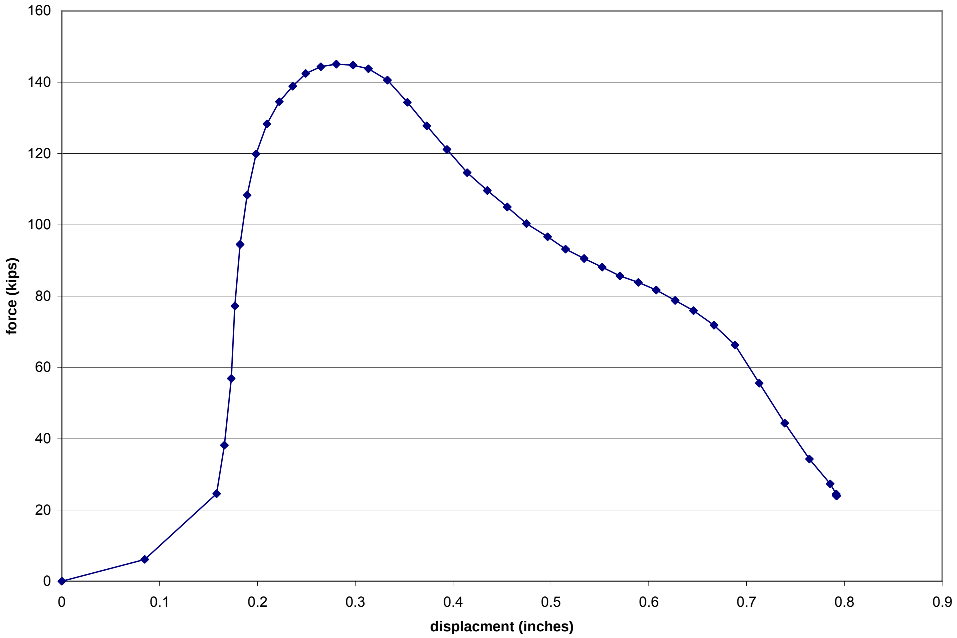


Figure A- 20 Force vs. punch displacement for Gr.50, 3/4" plate, 1/32" die cl.

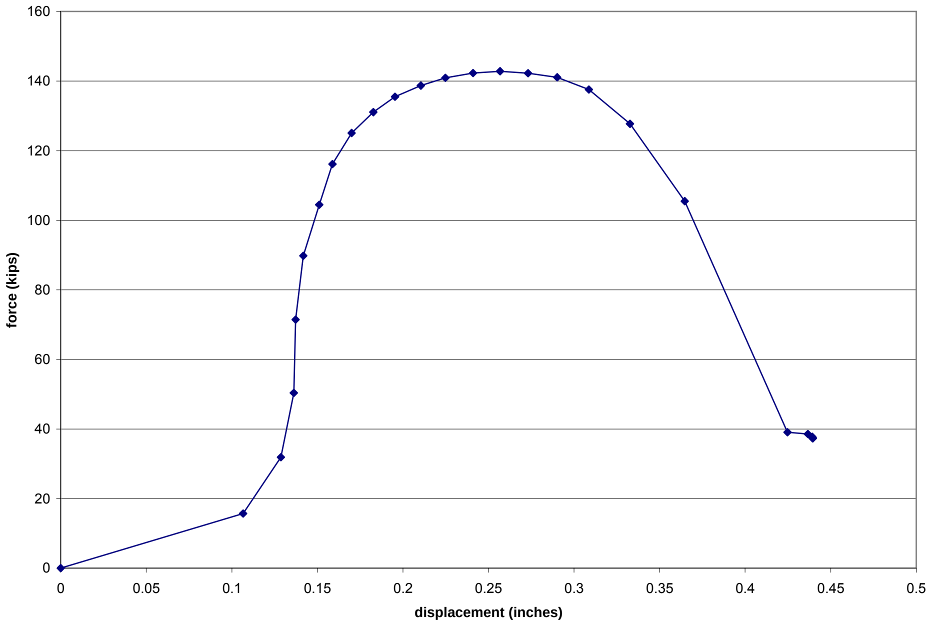


Figure A- 21 Force vs. punch displacement for Gr.50, 3/4" plate, 2/32" die cl.

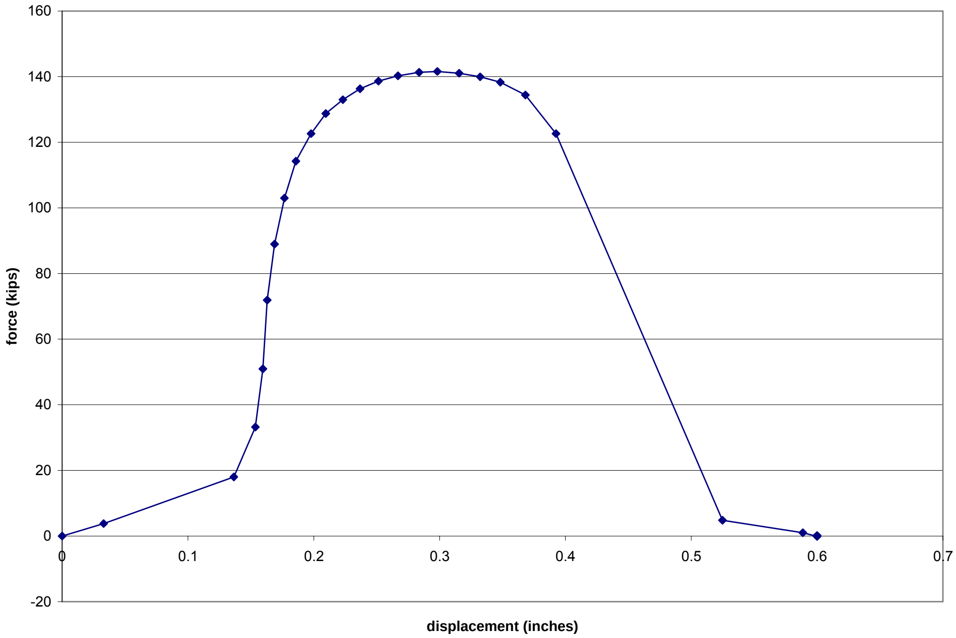


Figure A- 22 Force vs. punch displacement for Gr.50, 3/4" plate, 3/32" die cl.

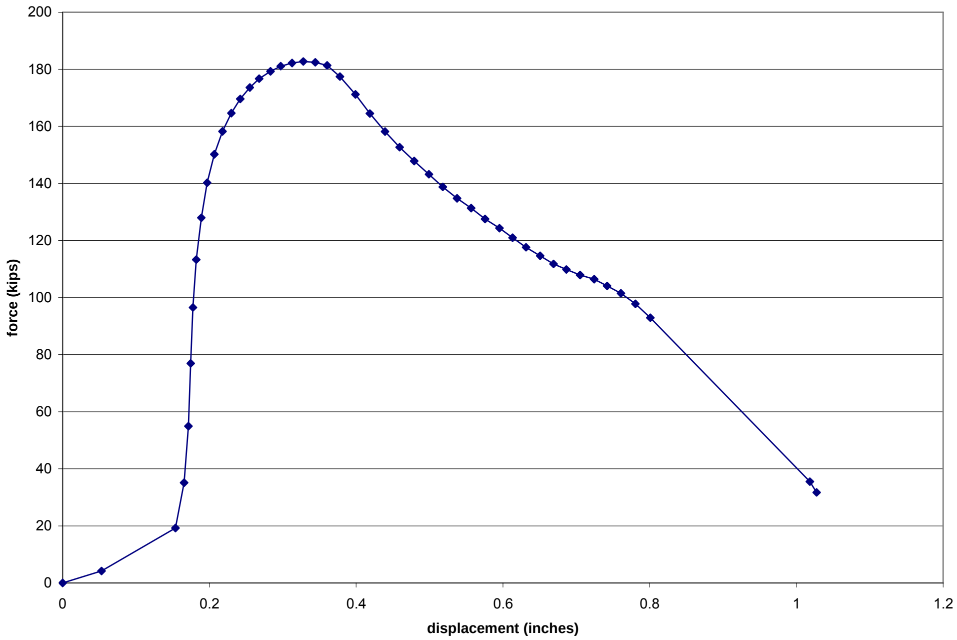


Figure A- 23 Force vs. punch displacement for Gr.50, 1" plate, 1/32" die cl.

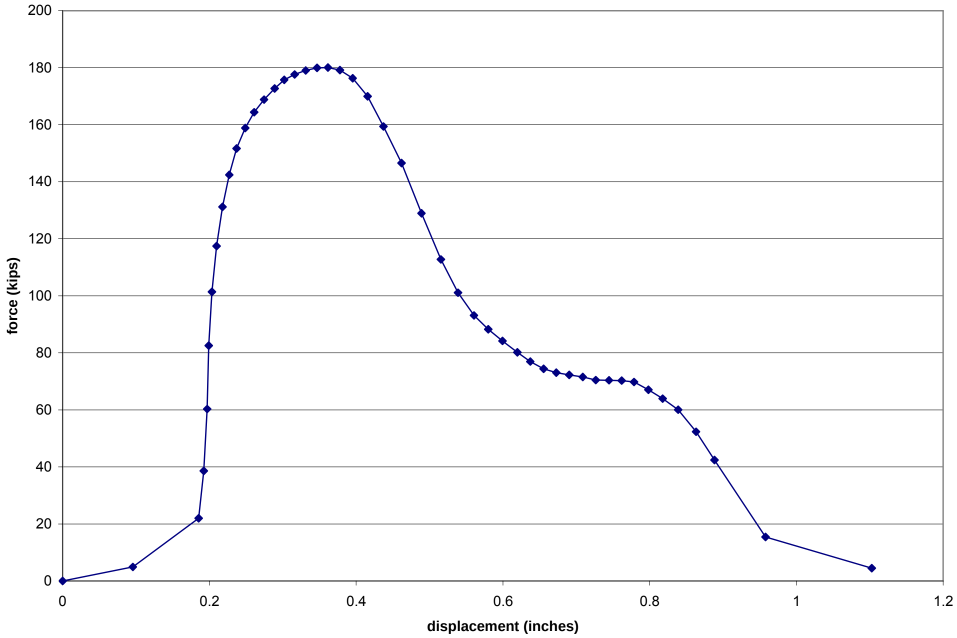


Figure A- 24 Force vs. punch displacement for Gr.50, 1" plate, 2/32" die cl.

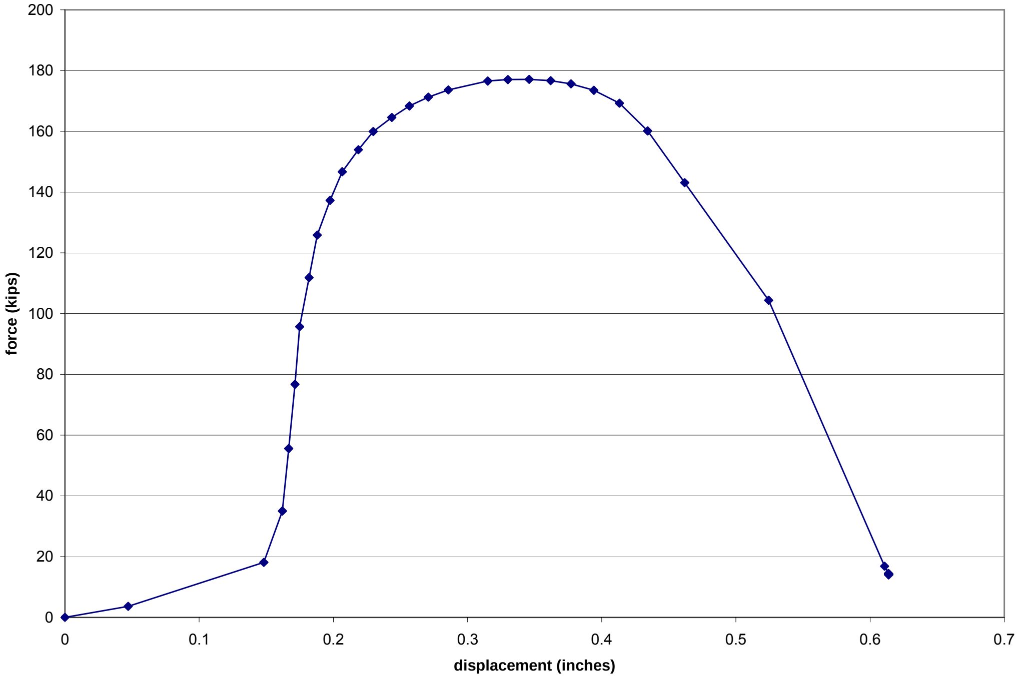


Figure A- 25 Force vs. punch displacement for Gr.50, 1” plate, 3/32” die cl.

APPENDIX B

Table B-1 Drilled oxy

Specimen	actual strength ratio	nominal strength ratio
Drilled oxy A36 1	1.004	1.003
Drilled oxy A36 2	0.981	0.976
Drilled oxy Gr50 3/8” 1	0.950	0.950
Drilled oxy Gr50 3/8” 2	0.888	0.870
Drilled oxy Gr50 3/4” 1	1.024	1.024
Drilled oxy Gr50 3/4” 2	0.930	0.930

Table B-2 Drilled plasma

Specimen	actual strength ratio	nominal strength ratio
Drilled plasma A36 1	0.972	0.930
Drilled plasma A36 2	0.947	0.931
Drilled plasma Gr50 3/8” 1	1.018	1.009
Drilled plasma Gr50 3/8” 2	1.015	0.988
Drilled plasma Gr50 3/4” 1	1.010	0.957
Drilled plasma Gr50 3/4” 2	1.030	1.017
Drilled plasma Gr50 3/4” 3	0.985	0.977
Drilled plasma Gr50 3/4” 4	1.044	0.971

Table B-3 Drilled

Specimen	actual strength ratio	nominal strength ratio
Drilled A36 1	1.047	1.047
Drilled A36 2	1.002	1.002
Drilled Gr50 3/8” 1	1.047	1.047
Drilled Gr50 3/8” 2	1.073	1.048
Drilled Gr50 3/4” 1	1.065	1.065
Drilled Gr50 3/4” 2	0.972	0.972

Table B-4 Long and short slotted punch holes and laser cut

Specimen	actual strength ratio	nominal strength ratio
Fabricators long slotted A36	0.956	0.952
Fabricators long slotted Gr50 3/8	1.006	0.982
Fabricators long slotted Gr50 3/4	0.905	0.905
Fabricators short slotted A36	0.972	0.972
Fabricators short slotted Gr50 3/8”	1.041	1.017
Fabricators short slotted Gr50 ¾”	0.931	0.931
Short Slotted A36 1	0.877	0.877
Short Slotted A36 2	0.967	0.950
Short Slotted Gr50 3/8” 1	1.034	1.020
Short Slotted Gr50 3/8” 1	1.039	1.029
Short Slotted Gr50 3/4” 1	0.915	0.915
Short Slotted Gr50 3/4” 2	0.946	0.946
Laser cut A36 1	1.003	0.976
Laser cut A36 2	0.907	0.907
Laser cut Gr50 3/8” 1	0.913	0.913
Laser cut Gr50 3/8” 2	0.924	0.924
Laser cut Gr50 ¾” 1	0.964	0.964
Laser cut Gr50 ¾” 2	0.967	0.967

Table B-5 Oxy full size

Specimen	actual strength ratio	nominal strength ratio
Oxy A36 1	1.007	0.999
Oxy A36 2	1.016	1.014
Oxy Gr50 3/8” 1	0.944	0.943
Oxy Gr50 3/8” 2	0.944	0.944
Oxy Gr50 3/4” 1	1.019	0.986
Oxy Gr50 3/4” 2	1.045	0.999

Table B-6 Plasma cut full size

Specimen	actual strength ratio	nominal strength ratio
Plasma A36 1	1.018	0.959
Plasma A36 2	1.015	1.010
Plasma Gr50 3/8” 1	0.986	0.972
Plasma Gr50 3/8” 2	1.014	0.973
Plasma Gr50 3/4” 1	1.038	1.020
Plasma Gr50 3/4” 2	0.936	0.927

Table B-7 Punched plasma

Specimen	actual strength ratio	nominal strength ratio
Punched plasma A36 1	0.966	0.903
Punched plasma A36 2	0.934	0.892
Punched plasma Gr50 3/8” 1	1.039	1.004
Punched plasma Gr50 3/8” 2	1.032	1.003
Punched plasma Gr50 3/4” 1	0.880	0.877
Punched plasma Gr50 3/4” 2	0.894	0.894
Punched plasma Gr50 3/4” 3	0.891	0.874
Punched plasma Gr50 3/4” 4	0.898	0.889

Table B-8 Punched oxy act

Specimen	actual strength ratio	nominal strength ratio
Punched oxy A36 1	0.919	0.919
Punched oxy A36 2	0.943	0.943
Punched oxy Gr50 3/8” 1	0.939	0.936
Punched oxy Gr50 3/8” 2	0.923	0.923
Punched oxy Gr50 3/4” 1	0.879	0.879

Table B-9 Punched (round) holes

Specimen	actual strength ratio	nominal strength ratio
Punched (round) A36 1	0.948	0.930
Punched (round) A36 2	0.908	0.908
Punched (round) Gr50 3/8” 1	0.996	0.986
Punched (round)Gr50 3/8” 2	1.022	1.019
Punched (round) Gr50 3/4” 1	0.839	0.839
Punched (round) Gr50 3/4” 2	0.892	0.892

APPENDIX C

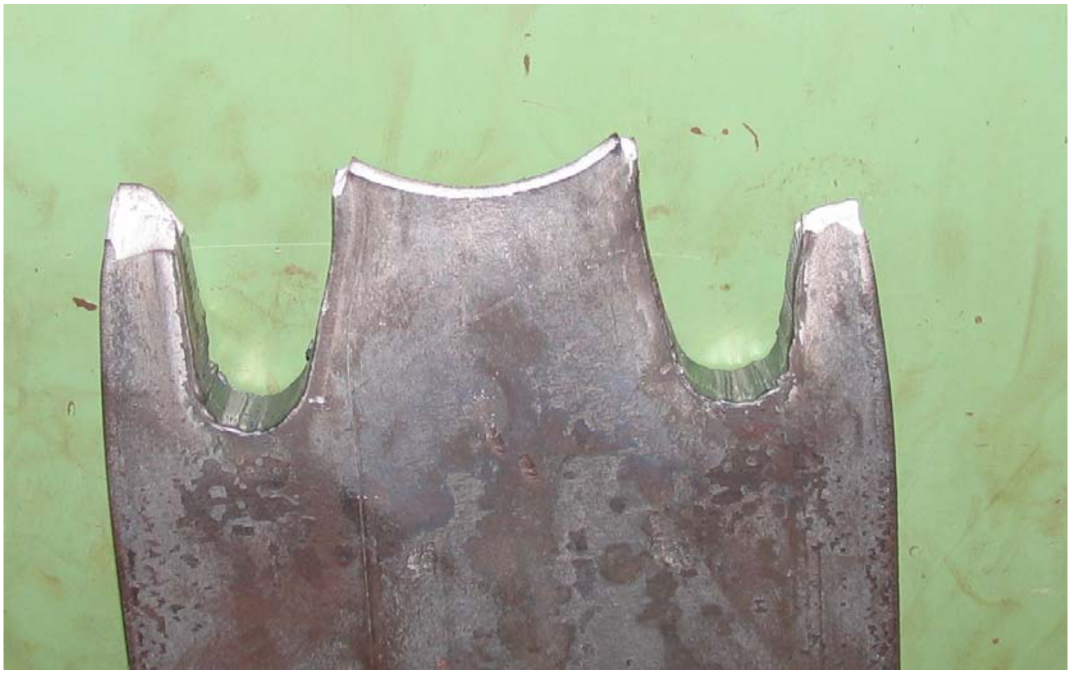


Figure C-1 Failure of Oxy act full size A36 ¾"specimen

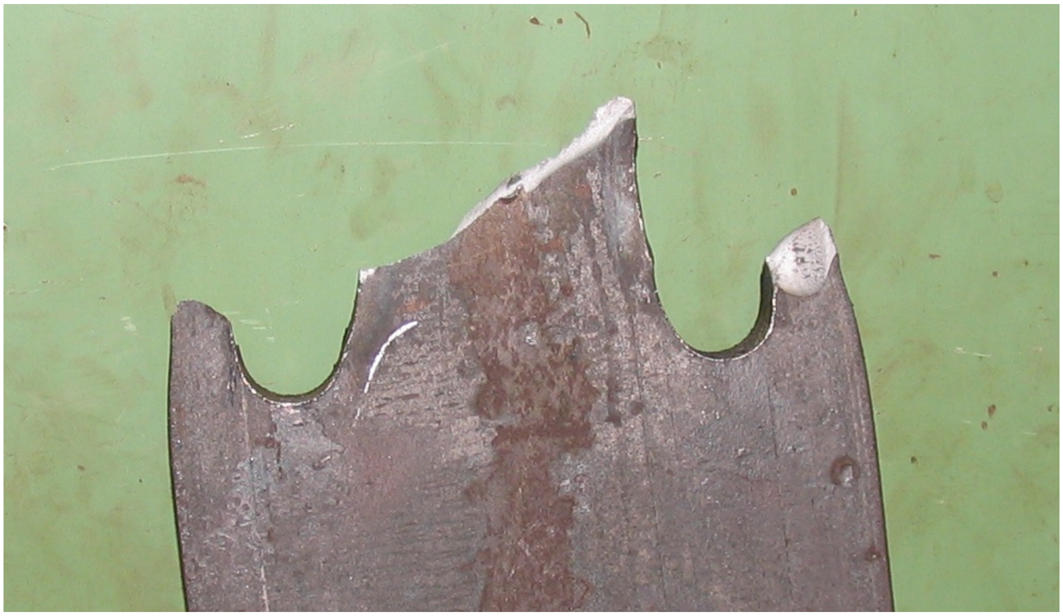


Figure C-2 Failure of drilled - oxy A36 ¾" specimen

Figure C-3 Failure of punched – oxy A36 ¾" specimen

Figure C- 4 Failure of drilled round A36 ¾"specimen

Figure C-5 Failure of punched round A36 ¾”specimen

Figure C-6 Failure of Punched full size Long slotted hole A36 ¾”specimen

Figure C-7 Failure of laser cut hole A36 ¾”specimen

Figure C-8 Failure of Plasma cut full size A36 ¾”specimen

Figure C-9 Failure of drilled plasma A36 ¾”specimen

Figure C-10Failure of punched plasma A36 ¾”specimen

Figure C-11 Failure of short slotted A36 ¾"specimen

Figure C-12 Failure of oxy act full size Grade 50 3/8"specimen

Figure C-13 Failure of drilled oxy Grade 50 3/8”specimen

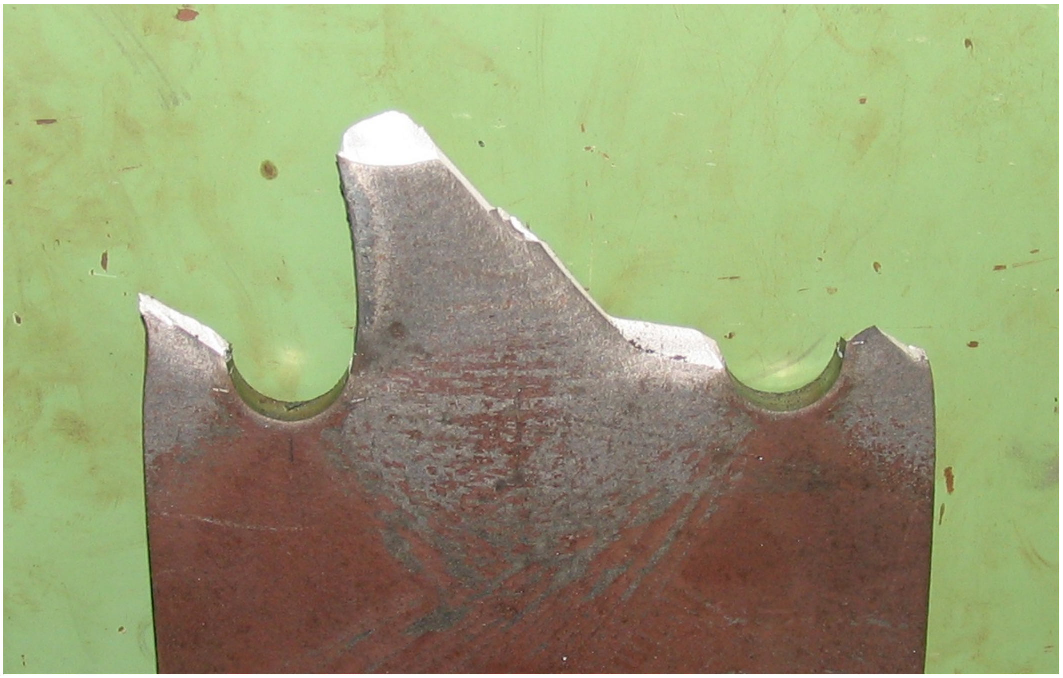


Figure C-14 Failure of punched oxy Grade 50 3/8”specimen

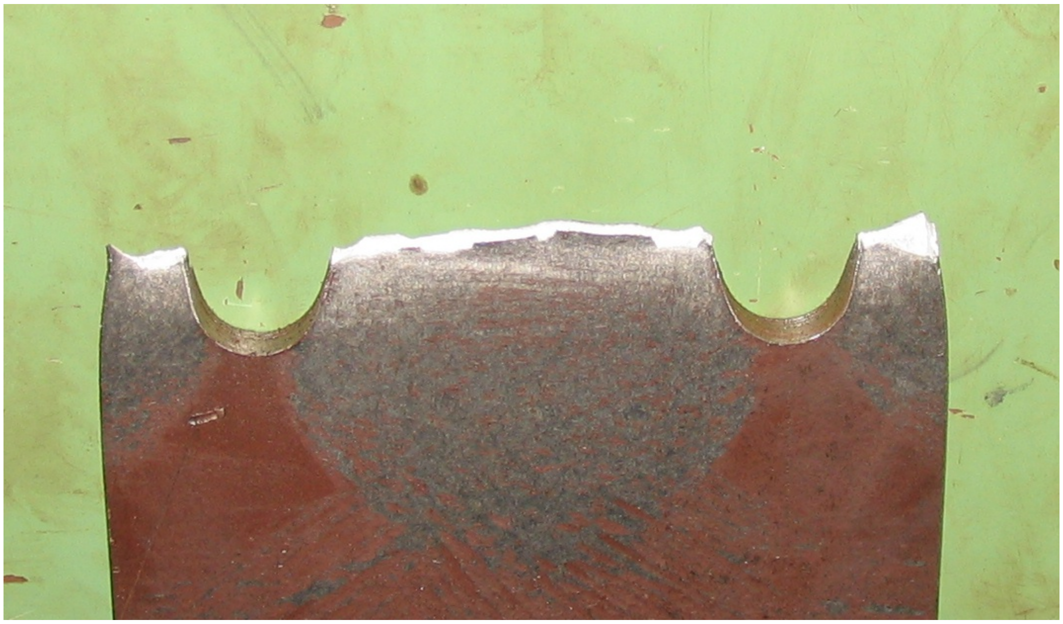


Figure C-15 Failure of drilled round Grade 50 3/8"specimen

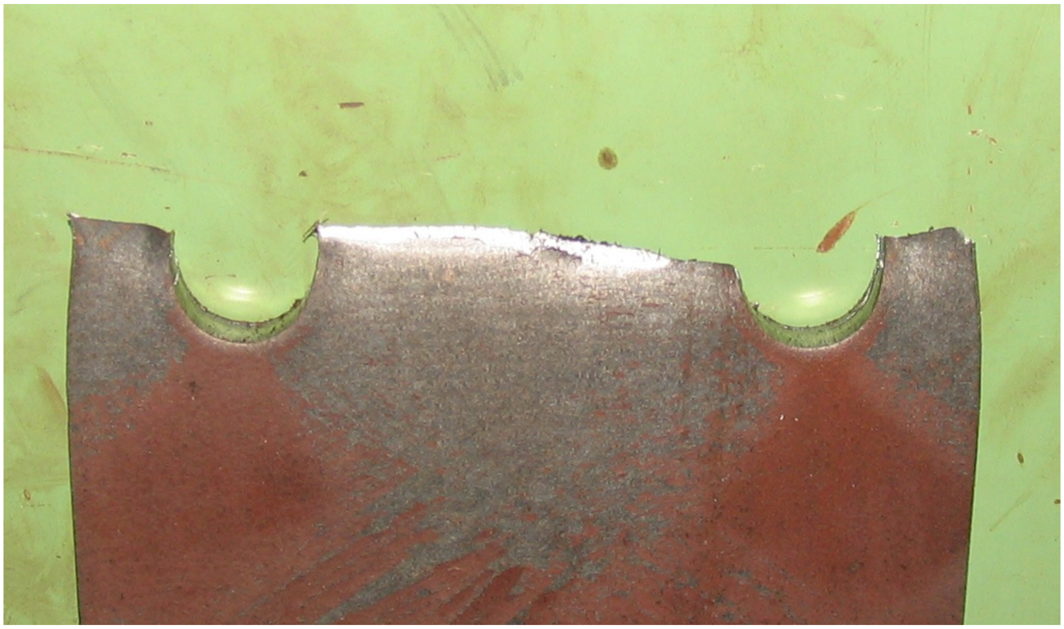


Figure C-16 Failure of punched round hole grade 50 3/8"specimen

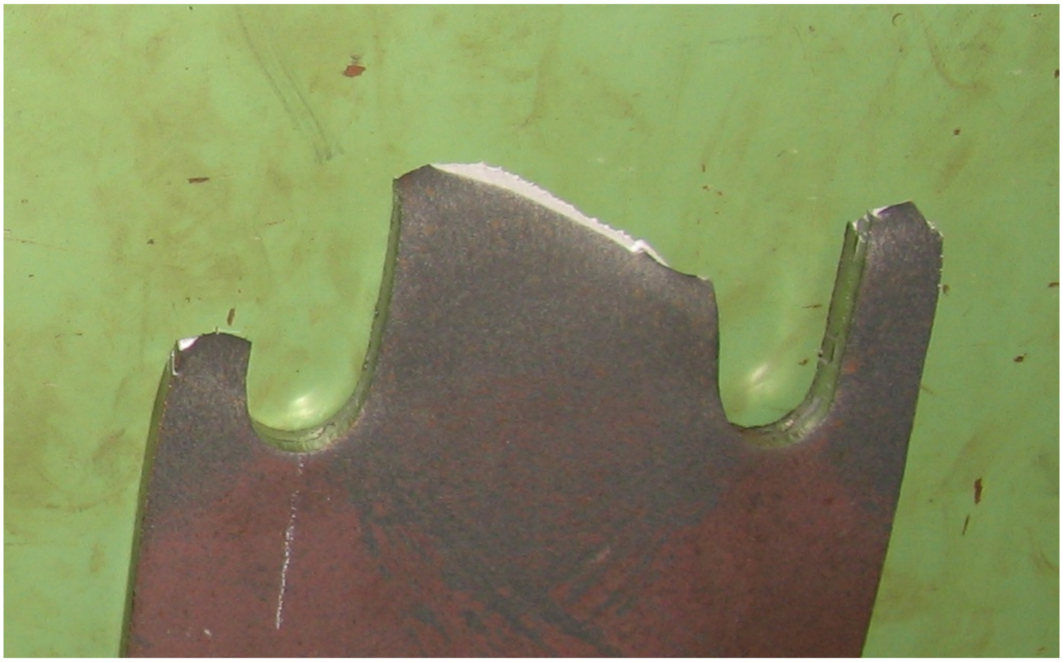


Figure C-17 Failure of Punched full size long slotted Grade 50 3/8”specimen

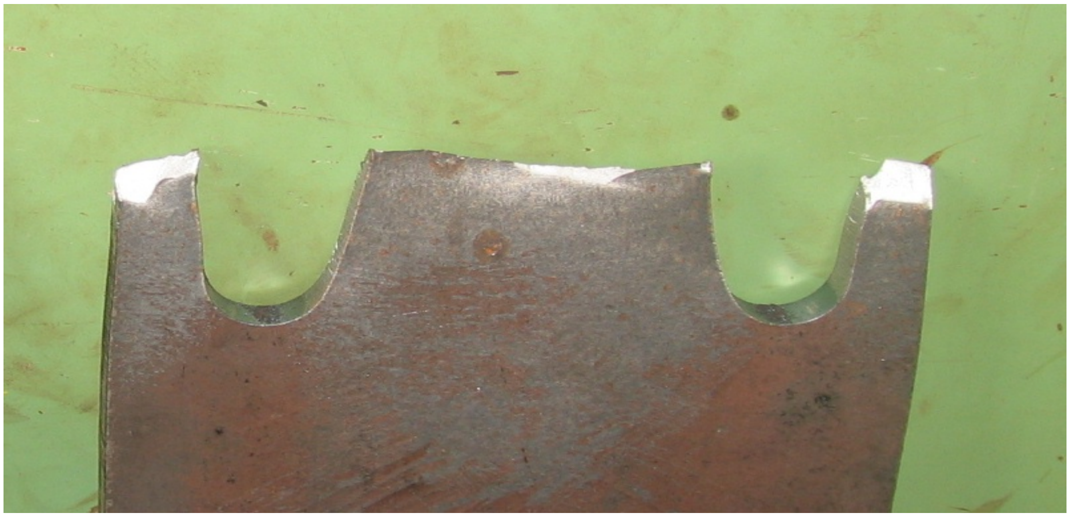


Figure C-18 Failure of Laser cut full size Grade 50 3/8”specimen

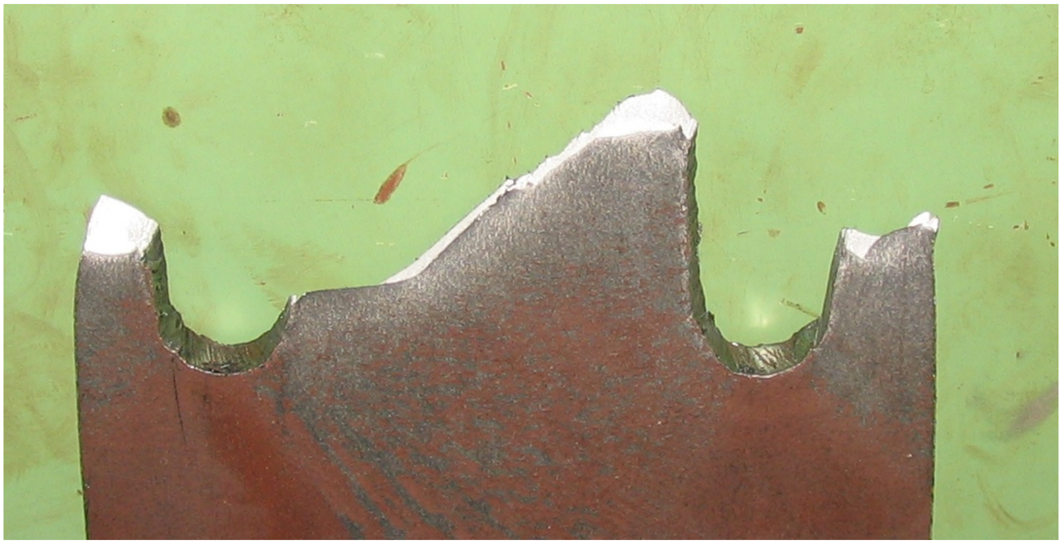


Figure C-19 Failure of Plasma cut full size Grade 50 3/8”specimen

Figure C-20 Failure of drilled plasma Grade 50 3/8”specimen

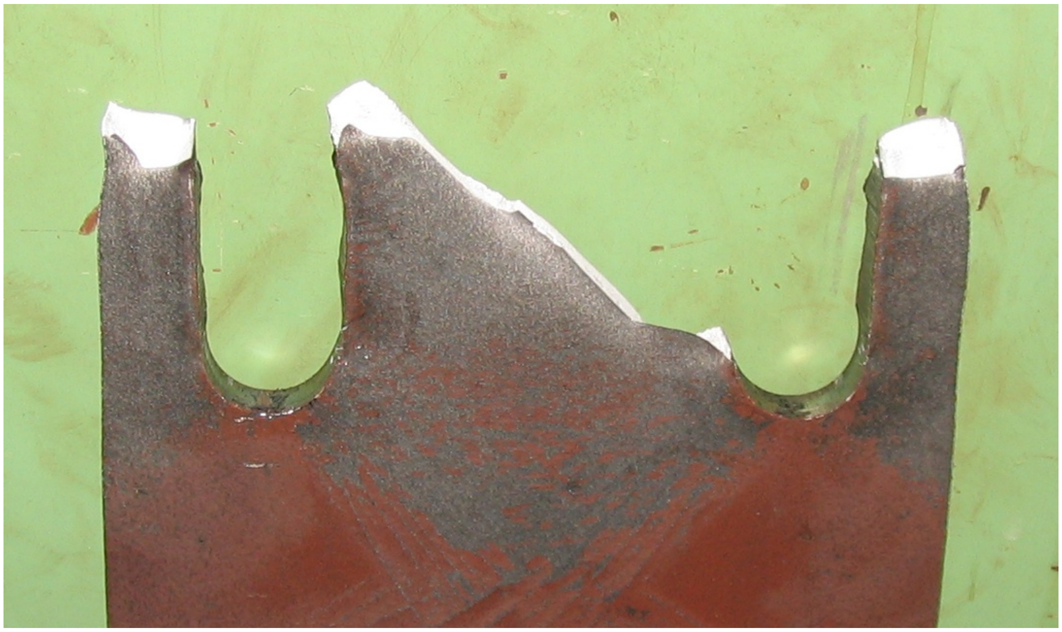


Figure C-21 Failure of punched plasma Grade 50 3/8"specimen

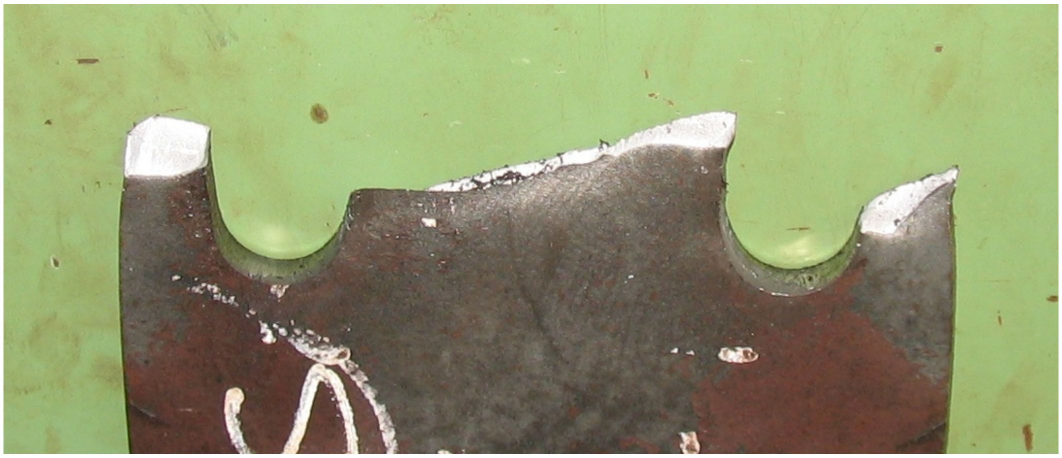


Figure C-22Failure of short slotted hole Grade 50 3/8" specimen

Figure C-23 Failure of drilled oxy Grade 50 ¾"specimen

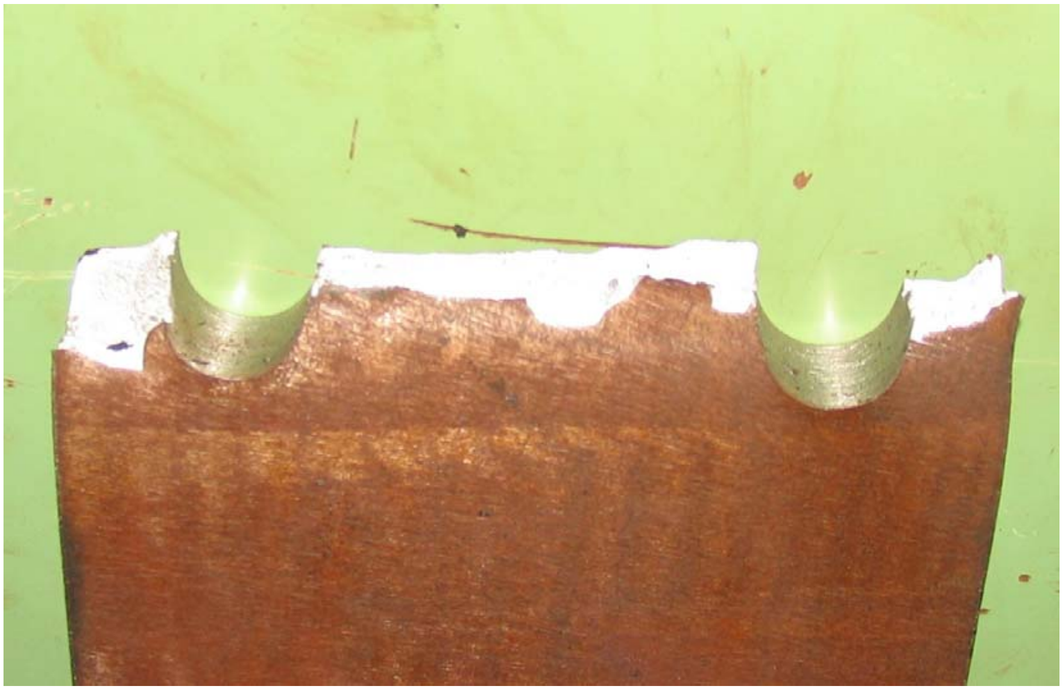


Figure C-24 Failure of drilled round hole Grade 50 ¾"specimen

Figure C-25 Failure of punched round hole Grade 50 ¾"specimen

Figure C-26 Failure of punched full size Grade 50 3/4"specimen

Figure C-27 Failure of laser cut full size Grade 50 ¾"specimen

Figure C-28 Failure of Plasma cut full size Grade 50 3/4"specimen

Figure C-29 Failure of drilled plasma Grade 50 ¾”specimen

Figure C-30 Failure of punched plasma Grade 50 ¾’specimen

Figure C- 31 Failure of short slotted holes Grade 50 ¾"specimen

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