6-1-1990

Feasibility Study of New Methods for Removing Rivets to Retrofit Railroad Bridges

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AT/LSS

ADVANCED TECHNOLOGY FOR
LARGE
STRUCTURAL SYSTEMS

Lehigh University

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ACKNOWLEDGEMENTS

This research was sponsored by the Canadian National Railway and conducted at the Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University in Bethlehem, Pennsylvania.

The authors extend their gratitude for the guidance of the project's advisory board: Mr. Roger Wildt (Bethlehem Steel), Mr. Edward P. Becker (Adjunct Professor of Civil Engineering at Lafayette College and Lehigh University), Mr. John McMahon (Institute of the Ironworking Industry), Dr. Robert A. P. Sweeney (Canadian National Railway), and Dr. John W. Fisher (Joseph T. Stuart Professor of Civil Engineering).

In addition, the authors greatly appreciate the time and energy of the ATLSS Laboratory personnel: Messrs. Bob Dales, Dave Kurtz, Michael Beaky, and Todd Anthony.

Acknowledgements are also due to Drs. Eric Kaufmann and Bruce Somers for their expertise in the area of material science.

Finally, the authors extend their thanks to Ms. Jane Birk who conducted a thorough literature review as part of the ATLSS summer REU program.

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EXECUTIVE SUMMARY

To maintain economic competitiveness, the Canadian National Railway would like to have the option of operating 120-125 ton capacity cars, an increase over the current 100 ton capacity. This increase in capacity will provide them with more flexibility in routing freight and, in many situations, will reduce the total cost. However, many of the bridges in the railroad system were not designed to carry the increased loads associated with the heavier cars. If the larger capacity cars are used, the gross weight will increase from 263,000 lb to 315,000 lb per car. The stresses on some riveted bridge members, generated by this increase in weight, exceed the constant-load fatigue capacity for Type C details. By replacing certain critical rivets with high strength bolts that have a higher shear strength, the bridges can be strengthened enough to carry the additional load.

For the Canadian National Railway, the cost to remove a rivet and replace it with a bolt has varied from $1.60 in the best case to $22.00 in the worst case. The majority of the replacement cost is the labor required to remove the rivet. An extremely difficult rivet could take as long as 35 minutes to remove. By designing a tool to reduce the amount of labor required, a significant reduction in cost could be achieved. With the large number of bridges in the Canadian National Railway System, a savings of a few dollars per rivet could easily translate into millions of dollars.

The objective of this research project was to develop concepts for an economical tool to remove rivets from railway bridges with the potential for significantly reducing the present cost of rivet replacement in the bridge girders.

Reviewed literature demonstrated that there have been a number of bridge rehabilitation projects which have utilized replacement of rivets with high-strength bolts as a means of strengthening a structure. The literature review revealed that pneumatic tools are the most widely used method for removing structural rivets. A summary of the literature review is available through the ATLSS Center. Unfortunately, there was no mention of any innovative techniques developed for structural rivet removal, and it remains apparent that due to the large number of riveted bridges needing repair in North America, a more economical and perhaps innovative approach would be readily accepted.

The researchers searched for some innovation by reviewing those patents pertaining to rivet removal tools. The tools focused on considerably smaller rivets associated with the shoe and aircraft industries and not on larger structural rivets. Copies of the patent abstracts are available through the ATLSS Center.

Based on the literature and patents reviewed, preliminary ideas for removing structural rivets were formulated. The project's advisory board assisted in condensing the list to seven removal methods. These methods or processes are Lasers, Hydraulics, Pneumatics, Liquid Nitrogen, Abrasive Water-jet Cutting, Powder Actuation, and Chisel Improvement. A detailed description of each can be found under the section labelled, "Investigated Techniques."

Rivets from the Grand Narrows bridge were used for experimentation. Comparison of results from Rockwell Hardness tests and Spectrochemical Analyses of rivets from the Grand Narrows bridge to results for rivets from the Queen Victoria and Beverly Viaduct bridges, in Canada, have proven that the Grand Narrows' rivets are representative of the rivets that the Canadian National Railway is replacing.

Information from Trexler Industries, a local laser cutting company, has revealed that a laser beam can only cut most effectively up to 1/8-inch thick material. The beam loses its intensity beyond 1/4-inch cutting thickness. Moreover, laser cutting causes heat buildup which develops substantial dross around the hole and requires a secondary finishing operation. For these reasons, as well as those of limited research time and money, the researchers decided to discontinue studies on laser cutting and to focus their efforts on more feasible developments.

A static load test, conducted on a section of a Grand Narrows' bridge girder, verified that hydraulics are powerful enough to remove most structural rivets. However, the force required to back out a rivet shaft from severe misaligned plates could be large enough to actually damage the girder. A hydraulic tool that could perform a rivet removal task quickly and with little effort would have to be large in order to provide the reaction force. Due to the existence of small clearances in most cases, the tool would not be feasible. For the purpose of removing the rivet heads only, a smaller hydraulic tool could be designed since a "scissors" cutting action would allow the applied and reaction forces to work together. Further tests would be required to verify that the tool would not slip from the rivets.

The Canadian National Railway's consistent use of pneumatic tools has demonstrated that pneumatics are quick and effective when they work, but require strenuous physical exertion. The weight of the tool results in substantial loss in actual removal time since an ironworker has to rest at frequent intervals. However, the weight is needed since it provides the mass to form a reaction force for the tool to work against.

A large pneumatic hammer, called a "rivet buster", was used for the geometry and chisel sharpness test. From the test results, it was found that one promising method to speed up the rivet removal process is to use the back out punch as a chisel. The back out punch removed the rivet heads quicker than the chisels. It also eliminated the time to change tools.

Another hypothesis was to alter the removal procedure so that a lighter pneumatic tool would prove sufficient. An example would be to use liquid nitrogen to make the rivets brittle, increasing the ease of their removal, and permitting a smaller impact force provided by a smaller pneumatic tool.

Experiments using liquid nitrogen have proven that rivets can be cooled to their ductile-brittle transition temperature inexpensively with little effort. The experiment demonstrated that an effective liquid nitrogen delivery system is essential. The system could be made portable since two pounds or less of liquid nitrogen are needed to make a rivet brittle. Tests were conducted to determine the time required to remove rivets at room temperature and below the ductile to brittle transition temperature. Unfortunately, the test results found no significant difference with the cooling. It has been hypothesized that the impact forces were not large enough to shear off the head with one or two blows. As multiple blows strike the rivet, it heats up and the temperature increases above the transition temperature. The question of local damage to the base material due to the use of liquid nitrogen followed by impact forces was not examined but should be if the method undergoes consideration.

A powder actuated tool, on the other hand, behaves just like a pneumatic hammer in that it delivers an impact force through a piston. The advantages over a pneumatic tool are that a powder actuated tool is self contained, lightweight, and relatively small. The disadvantage is that powder actuated tools would not have as high of a blows per minute rating as that of pneumatic tools. This results in slower removal rates. The cost of supplying the powder cartridges was also considered to be more expensive than an air supply.

Waterjet cutting experiments indicated that an abrasive waterjet tool would be feasible to remove rivets in plates less than 1-1/2 inches thick. Beyond this distance the feed rate is significantly reduced and the distortion increased. Although the procedure is effortless, it takes about 5 minutes to remove a rivet. Yet a standard rivet diameter makes an automated system utilizing waterjets very feasible. An automated system could operate more than one waterjet to increase the production rate. In situations over 1-1/2 inches thick, it might be feasible to design a tool to travel into the rivet hole as it cuts to prevent jagged edges. It is probable that this method would remove rivets faster because the nozzle would always be close to the base material, a condition which significantly increases cutting effectiveness.

The waterjet cutting experiment also indicated that the danger of the powerful waterjet stream could be more easily contained than anticipated. It could cut through human flesh over 15 feet away from the nozzle but would not damage metal beyond several feet since the cutting effectiveness of the stream dissipates considerably as the distance from the nozzle increases. The stream flowing out of the cut, as observed in the experiment, would not damage adjacent girders.

Upon examining our results, it appears that abrasive waterjet cutting shows considerable long term promise for removing structural rivets. Abrasive waterjet technology is developing quickly and within the next five (5) years, a more efficient abrasive waterjet cutting system should be readily available to retrofit railway bridges.

In the meantime, use of a pneumatic hammer is expected to continue, but with evaluations of different tool (chisel/punch) configurations to simplify the rivet removal process.

INTRODUCTION

Objective

The objective of this research project was to develop concepts for an economical tool to remove rivets from railway bridges with the potential for significantly reducing the present cost of rivet replacement in the bridge girders. To do this new methods and processes to remove structural rivets from railway bridges were investigated and the costs associated with these methods were compared to the traditional method of using a pneumatic rivet buster. Some of the methods were deemed infeasible from the literature, analysis of the application, or talking with experienced researchers. Others were investigated in a laboratory setting to determine their feasibility. Each technique is discussed in this report, the laboratory data are included where applicable.

Background

In order to maintain economic competitiveness, the Canadian National Railway would like to have the option of operating 120-125 ton capacity cars, an increase over the current 100 ton capacity. This increase in capacity will provide them with more flexibility in routing freight and, in many situations, will reduce the total cost. However, many of the bridges in the railroad system were not designed to carry the increased loads associated with the heavier cars. If the larger capacity cars are used, the gross weight will increase from 263,000 lb to 315,000 lb per car. The stresses on some riveted bridge members, generated by this increase in weight, exceed the constant-load fatigue capacity for Type C details. By replacing certain critical rivets with high strength bolts that have a higher shear strength, the bridges can be strengthened enough to carry the additional load. The critical rivets are those in the middle 20 percent of the span along the bottom flange of the girders. On an average bridge, this translates to about 15 feet of rivets or about 100 rivets.

For the purpose of this study, the railroad bridges can be divided into two groups: those in the western region and those in the eastern region. Most of the bridges in the western region were built in the time span from 1908 to 1915. In general, they were built to better specifications than their U.S. counterparts. The steel produced at this time was very close to U.S. ASTM A-7 steel with a yield strength of about 30 ksi. Some of the eastern region bridges were built with Bessemer steel. However, this study will focus on the steel most commonly found in the western region. Currently, there is a C detail on the bottom flange of the girders. The goal of the Canadian National Railway is to achieve a B detail.

Most of the original rivets were 7/8 inch. The girders were sub-punched and reamed or drilled to 15/16 inch prior to the installation of these rivets. Some of the joints have many plies which makes it difficult to punch out the rivets when the holes in various plies are misaligned. Also, some of the rivets are close to the flange and have a clearance of only 1-1/4 to 1-1/2 inches. This could cause access problems for a tool and must be considered in the study.

For the Canadian National Railway, the cost to remove a rivet and replace it with a bolt has varied from $1.60 in the best case to $22.00 in the worst case. The typical cost for a western bridge is $13-$14 per rivet and for an eastern bridge is $5.00-$8.00. The lower cost in the east is primarily due to better track time. The majority of the replacement cost is the labor required to remove the rivet. An extremely difficult rivet could take as long as 35 minutes to remove. By designing a tool to reduce the amount of labor required, a significant reduction in cost could be achieved. With the large number of bridges in the Canadian National Railway System, a savings of a few dollars per rivet could easily translate into millions of dollars.

Research Team

The research team was composed of the principle investigator, Dr. Gregory L. Tonkay, Assistant Professor of Industrial Engineering; Linda Falcone, an ATLSS Graduate Student; and Edward P. Becker, an Adjunct Professor of Civil Engineering. This team was guided by an advisory panel. The panel was composed of the research team members; Dr. Robert A. P. Sweeney of the Canadian National Railway; John McMahon, Executive Director of III (Institute of the Ironworking Industry); and Roger Wildt, Manager of Construction and Marketing at Bethlehem Steel Corporation. The latter two members have considerable industrial experience in the area of rivet removal. The advisory panel was responsible to oversee the research and provide suggestions based on their broad experiences.

Current Method of Rivet Removal

The current method to remove rivets is to knock off the head using a pneumatic "rivet buster" and then force the rivet shaft out using a back out punch mounted in the same tool. Once the rivet is removed, the hole is drilled out (if needed) and a high-strength bolt is inserted and tightened using the turn-of-the-nut method. On a recent job less than ten percent of the holes required drilling prior to bolt insertion. No means of recovering the rivet head or shaft are being employed at the present time.(1)

Considerations in Tool Selection/Development

The following considerations need to be kept in mind concerning selection and/or development of a rivet removal tool (2):

- **Speed.** The purpose of this project is to reduce the average time needed to remove and replace each rivet.
- **Cost.** In addition to labor cost related to the speed of a rivet removal tool, additional costs such as capital cost, maintenance cost, and material cost, must be economically justified.
- **Non-destructiveness.** The method chosen should avoid the risk of damage to the steel girders.

- **Size**. The rivets to be removed are often close together and/or close to the web or stiffeners. Therefore, the size of the proposed tool is important.

- **Weight/Maneuverability**. Since the operation may be performed by two men in a small bucket, the weight and maneuverability of the tool is important.

- **Set Up/Tear Down Time**. The time between trains is normally about four hours. The time available for actual rivet removal is limited by the amount of time necessary for arrival, set up, tear down, departure and a safety margin. The set up and tear down times should be as short as possible to allow the maximum amount of time to be spent on actual rivet removal.

- **Safety**. The work is sometimes done in rather remote areas, at high elevations, over water, and is time dependent upon train schedules; therefore the safety of the workers is of concern.

SUMMARY OF THE LITERATURE REVIEW

Past Methods

The literature review conducted during the early part of the project demonstrated that there have been a number of bridge rehabilitation projects which have utilized replacement of rivets with high-strength bolts as a means of strengthening a structure. The literature review revealed that pneumatic tools are the most widely used method for removing structural rivets. Acetylene torches and high-speed drills have also been used but they are not as prevalent as pneumatic tools. The following is a summary of the findings. A more detailed review is available through the ATLSS center.

Dr. Harold S. Reemsnyder has conducted rivet removal studies at Bethlehem Steel. In his 1985 paper called "Fatigue Life Extension of Riveted Connections," he documents the study showing that fatigue life of ore bridges could be extended by replacing rivets with high strength bolts. Reemsnyder indicated that

> "... the rivets were removed with a pneumatic hammer and backing-out punch. The rivet head was knocked off with the hammer held at a flat angle with respect to the channel web. The remainder of the rivet was then driven out of the connected plies. This method ... was developed for field rivet removal and does not damage the connected material."(3)

The same pneumatic tool, fitted with a round punching head, was used for both the rivet head removal and the punching operation. This technique, using air-powered tools, was used to replace critical riveted connections in all ore bridges at the Bethlehem Steel site. Dr. Reemsnyder acknowledges C. E. Adamcik and D. H. Hall, Engineering Department, Bethlehem Steel with development of the rivet removal technique.(4)

In general, the articles reviewed under "past methods" can be categorized into three different groups:

- Those making reference to Reemsnyder's report and rivet removal methods.

- Those indicating the use of other methods, such as drilling or burning. Most of these articles did not explain the rivet removal procedures in detail; however, some commented on their disadvantages.

- Those verifying the means to strengthen bridges by removing critical rivets and replacing them with high strength bolts. In these articles, no significant details about the rivet removal procedures were provided.

In addition to rivet removal on steel bridge structures, additional information was found concerning the removal of smaller rivets and nails from materials other than steel. Although these articles do not relate directly to the present project, they may be useful in the development of a new tool.

Most of these articles outline a robotic system being developed by Southwest Research Institute (San Antonio, TX) for removing rivets from airplane wings. The system uses an electrically driven robot. The rivet head is precision drilled and the shank is removed by a punch driven by a pneumatic hammer (3 punches are available on the system). The drilling apparatus is designed such that it can drill all expected rivet sizes without changing tools.

From the literature reviewed, it appears that three basic methods of rivet removal have been utilized (5):

- **Pneumatic Tools.** Pneumatics are the most widely used. The method has been used successfully for many years. Its most notable use is probably that of Bethlehem Steel in the strengthening of its ore bridges as outlined in the Reemsnyder report. This report has been referenced in numerous other repair jobs. (Morris, 1978; Soto, 1978; Szeliski & Elkholy, 1984; Vaidyanathan, 1978.)

- **Acetylene Torch.** Although this quick method of rivet removal has been in existence for a long time, its use requires extreme care and a very skilled operator. There also exists a danger that the steel will be accidentally damaged. This danger is well documented in the literature. (AREA, 1950 and 1955.)

- **Drilling.** This method is only mentioned for one bridge repair project (Marine Parkway) and the exact procedure is not specified. Drilling is often used to remove smaller rivets, but may become very time consuming when applied to large structural rivets. (Martin & Iffland, 1983.)

Unfortunately, there was no mention of any innovative techniques developed for structural rivet removal, and it remains apparent that due to the large number of riveted bridges needing repair in North America, a more economical and perhaps innovative approach would be readily accepted.

Based on the literature search for past methods of rivet removal techniques, preliminary ideas for rivet removal methods were formulated with their advantages and disadvantages. Additional ideas formulated by the project's advisory team have been appended to the following list:

- **Knock and Punch**. This is the current method. The process of knocking off the rivet head may result in a distortion of the remaining shaft. If the shaft is no longer round because of misalignment of the plies, it is difficult to push the distorted shaft through the round hole. In addition, the force required to punch the rivet out results in a lateral expansion of the rivet shaft, possibly further wedging it into position.

- **Drill Out**. Drilling is time-consuming, considering the diameter of the rivets. Diamond-pointed drilling tools might speed the operation, but they require coolant for operation which may be impractical in the field. Also, the rotation of the drill may cause the rivet to spin once the gripping force is released.

- **Use Coring Tool**. The rivets may be too small for effective use of coring tools. In addition, the misalignment of plies may also cause an orientation problem for the coring tool possibly enlarging the hole or damaging the steel.

- **"Bite" Off Head in Tension, Then Punch Out**. The head could be pulled off in tension using a staple-puller type device. This would result in a remaining shaft with a smaller cross section. This would allow for some expansion of the rivet before it would again fill the hole, lessening the problem of further impacting the rivet while trying to drive it out.

- **Grind Off Head, Then Push Out**. The head could be ground flush with the girder and then knocked out with a punch. This method would eliminate any deforming of the shaft caused by knocking off the head. A problem with this method is possible damage to the girder caused by the grinder. In addition, this method would consume much time.

- **Pull Out**. The "back" head of the rivet would be removed and a stud welded to the "front" head. The stud could then be used to pull out the shaft using an electric, hydraulic or pneumatic device. Alternately, depending upon the geometry of the "front" head, the rivet possibly could be pulled out directly using a staple-puller type device. Problems with these methods include the strength of the weld, the cost of the welding procedure, and the possibility that the rivet would fracture prior to being pulled out.

- **Burn Out**. Use an acetylene torch to remove the rivet head and shaft. Experience has shown that there should be no metallurgical damage to the girder due to the heat involved; however, there is the possibility of damage to the girder due to accident or improper removal technique.

- **Cut/Drill/Punch**. The rivet head is first cut off and then a hole smaller than the rivet diameter is drilled partially through the rivet's grip. The drilling process weakens the rivet, making it easier to push it out using a punch. Considerations on using this method include the need for several tools (cutter, drill and punch) and the speed with which the rivets can be drilled. The drilling process must be rapid to make this idea cost-effective. Also, as with drilling the entire rivet out, the rotation of the drill may cause the rivet to spin once the gripping force is released.

- **Controlled Burning**. This method is a combination of the cut/drill/punch method substituting a controlled burning in the center of the rivet for the drilling operation. The acetylene torch could be used for both cutting off the rivet head and weakening the shaft, thereby reducing the number of tools needed. This method would be faster than drilling, but carries the risk of accidental damage to the steel girders.

- **Shrink Rivet**. Liquid nitrogen could be used to shrink the rivet prior to attempting removal. Possible problems with regard to use of this method include the embrittlement of the steel girders due to the low temperature, cost of use in the field and safety.

- **Laser**. Use a laser beam to remove the rivet head and shaft. Concerns with this method would be the cost of use in the field, the heat affected zone it creates, a required finishing operation and safety.

- **Pneumatics**. The air pressure can be varied to take advantage of the natural frequency of the rivets and increased to provide additional power to force out an extremely difficult rivet. In addition, pneumatic hammers can provide more power in a smaller package than electric hammers.

- **Hydraulics**. Canadian National Railway has never used hydraulics for rivet removal. Hydraulics may be useful in the development of a rivet removal tool since it can deliver the powerful forces needed in a punching operation.

- **Pneumatic/Hydraulic Combination**. A single power supply could be constructed to deliver both air and fluid power. Similarly, two separate power supplies could be used. A combination pneumatic/hydraulic system could combine the advantages of both technologies.

- **Powder Actuation.** A powder actuated impact tool could offer a lightweight and flexible alternative to pneumatics or hydraulics for the purpose of removing structural rivets.

- **Waterjet Cutting.** A high-speed water stream could be used to cut the rivet out of its hole. Furthermore, the waterjet could ream holes that require reaming.

- **Automation.** Design of an automated device utilizing one or more of the above-mentioned methods. The device would have to be light and involve a short set-up and tear-down time to be feasible. Concerns associated with designing such a device include the differences in the riveting patterns, different rivet diameters, number of plies, grip lengths, and rivet head conditions.

Patent Search

A patent search was initiated through the law offices of Ratner & Prestia on August 8-9, 1989. The search covered United States patents spanning the period from 1963 through May 1989. The search was limited to patents containing a reference to rivet removal in their titles. Copies of the patent abstracts of these inventions are available through the ATLSS center.

A search through the alphabetical indices available in the Lehigh University Library (1920 through 1953) yielded numerous rivet removal devices, mechanisms and schemes.

The researchers searched for some innovation by reviewing those patents pertaining to rivet removal tools. The tools focused on considerably smaller rivets associated with the shoe and aircraft industries. The tools that may be of some conceptual interest to the researchers are listed below (6):

- Apparatus for Cutting Rivets of Tension Reinforcement in the Process of Manufacturing Concrete Products. (Cuts rivets from rebar.)

- Rivet Removing Tool (DalBianco). Cores head from rivet so that shank can be removed.

- Rivet-Breaker (Nurnberger), Rivet Breaker (Keller), Rivet Cutting Gun (Stevens), Rivet Remover (Temple), Rivet Cutter (Burns), Rivet Removing Device (Rocheville). Pneumatic devices.

- Apparatus for Removing Rivets from Structures (Ames).

- Rivet Cutter (Barnes), Rivet Cutter (Arn), Rivet Stem Puller and Cutter (Mellerio). Devices using "jaws" to sever rivet head.

- Rivet Remover (Kanihan). Drilling device.

The most innovative technique found relies on a robot that removes and replaces aircraft rivets. Considering the rapid growth in the number of bridges needing repair and the hundreds of rivets associated with each bridge, the task may justify the use of an automated system, such as a robot.

INVESTIGATED TECHNIQUES

Upon reviewing the literature, patents, and preliminary list of ideas, the researchers and advisory board formed a list of seven alternatives. The researchers investigated each technique and a description of each follows.

Lasers

Laser cutting's rapid growth among nontraditional machining processes during the past decade initiated investigation into lasers and its possible application to structural rivet removal. The investigation included a literature review of the laser cutting process, information from the president of Laser Applications, Inc. (LAI), and second-hand information from a local laser cutting company, Trexler Industries.

Lasers offer an advantage for the manufacturing world. With changes in its power density, the laser can be made to perform several tasks, including cutting and even welding. A laser is capable of processing all known material when it can be focused to generate 10^9 watts/in^2 at the focal point. Cutting carbon steel requires a laser power density of 10^7 watts/in^2. Cutting through rivets which are produced from low carbon steel would require more power because the steel lacks oxygen, an assist gas of the cutting process.

The researchers were interested in the speed of the laser cutting process as well as its cutting depth capabilities. Lasers can cut through 1/8 in. (3.2 mm) carbon steel in a matter of seconds; however, the literature review revealed that lasers are utilized for cutting relatively thin material since they are most effective for cutting carbon steel below 1/8-inch. "Classification of Materials," an article in the February 1989 issue of Manufacturing Engineering, states that steel thicker than 1/8-inch has striations on the cut edge.(7) In addition, this steel is assumed clean of rust or dirt. Furthermore, lasers create a heat affected zone by inheriting the problem of heat build up and substantial dross that adheres to the cutting edge requiring a secondary finishing operation. The thicker the material, the greater the problem with surface finish. Portable laser systems have not been commercially developed and would require a substantial investment to build a prototype system.

Finally, in order to perform the rivet removal task, the laser beam would be required to remain extremely steady. Such a requirement suggests a robotic or automated system with a relatively high development cost. Because of all the physical limitations involved in this process, it was deemed infeasible.

Hydraulics

Hydraulic tools are inexpensive relative to high technological cutting processes like lasers, yet are known for exertion of powerful static forces. Hydraulic tools for application to structural rivet removal could be designed for any of the following three purposes: to remove the rivet head only; to remove the rivet shaft only; or to remove both.

For any tool which uses static force, a reaction force must be provided. The larger the application force, the larger the needed reaction force and the larger the size of the tool. For the purpose of removing a rivet head, the researchers envisioned a hydraulically operated tool consisting of two "jaws" that could grab the rivet head, apply a "scissors" action, and essentially pull it off. The application force would be provided by one jaw and the reaction force by the other. Consequently, the two jaws work together to shear off the rivet head. Depending on the forces required to shear off the rivet head, this method could prove feasible.

On the other hand, a pushing force required to remove a rivet shaft would require a tool to clamp on the girder in order to provide the reaction force. This requirement could cause some potential problems. First, the reaction and application forces would oppose each other creating some potential damage to the girder. Second, since some of the rivets are difficult to access (close to the web or other girders), it would be difficult to produce a design usable in all situations. Because of the magnitude of the force required, the hydraulic tool would probably be large and heavy.

It would be ideal to produce a hydraulic tool to accomplish both the rivet head and rivet shaft removal tasks. However, due to the physical differences in the tasks and the problems discussed previously, the design of a single tool would be difficult if not infeasible. As a result, it may be more feasible to develop a hydraulic rivet head removal tool and use it in conjunction with another method effective in removing the rivet shafts.

This method was deemed possible and worth investigating further in the laboratory. Data were required about the amount of force required to accomplish each removal task. Later, these forces could be extrapolated back to the design of a hydraulic tool putting the researchers in a position to determine feasibility.

Pneumatics

Pneumatics are capable of removing structural rivets by delivering powerful repetitive impact forces on a rivet. Because air is compressible, large amounts of air are required to generate the pressures to produce large static forces. In fact it is difficult and expensive to achieve high pressures with air. Instead, pneumatic tools provide an impulse force by moving a mass, such as a chisel, at a high velocity and striking it against the object to be chiseled. Just like hydraulic tools, a reaction force is required with pneumatic tools. However, since the force is an impulse, a large mass can be used as the reaction force. For this reason pneumatic hammers, also called rivet busters, are very heavy.

Pneumatic hammers have demonstrated their effectiveness in the field and have been used to remove structural rivets for many years. Among the other current structural rivet removal techniques, such as high speed drilling and acetylene torches, pneumatic hammers remain the most successful. Pneumatics are also less expensive than hydraulics. All of these reasons explain why the Canadian National Railway presently uses this method to remove structural rivets from their railway bridges.

Pneumatic tools for structural rivet removal applications have several disadvantages. Pneumatics produce extensive vibrational forces and noise that expose frequent operators to potential hazards. In addition, the impact forces are counteracted through rigid steel tool construction. As a result, a pneumatic tool strong enough to deliver the forces required to remove structural rivets weighs from 30 to 40 lbs. The weight of the tool when used throughout the day results in operator fatigue which decreases productivity. Typically, only a handful of rivets can be removed at a time before the operator needs to rest.

The advisory panel suggested that the research team should consider redesigning the hammer more efficiently for the structural rivet removal task. However, based on the previous discussion it was decided that it was critical for the tool to have a large mass to counteract the impulse blows. Smaller, lighter-weight tools were tried which did not remove the rivets at all. No design could be found that would make the tool easier to handle while maintaining the flexibility and effectiveness.

Another suggestion consisted of reducing the amount of force required to remove a rivet and thus the weight of the tool. One possible method of reducing the force requirements is described in the next section.

Liquid Nitrogen

A method proposed for simplifying the rivet removal process by reducing the required removal forces was to use liquid nitrogen to cool a rivet to its brittle temperature before removing it with an impact tool. Liquid nitrogen should make the rivet brittle thus reducing the amount of impact energy required to remove the rivet head. Ultimately, the use of liquid nitrogen could possibly permit a smaller pneumatic (impact) tool.

Literature search identified two applications of liquid nitrogen. An article in the December 1985 issue of Cryogenics entitled "Liquid Nitrogen Unit for Cryosurgery" introduced a compact and transportable device used to destruct diseased body tissue as well as highly vascular and malignant tumors. The device known as the Spembly autoclavable cryoprobe "applies the intense freezing power of liquid nitrogen at -196 degrees celsius to target tissue via an easily and accurately controlled vacuum-insulated probe."(8) Spembly Medical has an extensive range of other cryosurgical instruments including small, lightweight hand-held units as well as comprehensive systems.

An additional application of liquid nitrogen involved the simplification of removing several layers of paint for the renovation of the Statue of Liberty in 1984. The method employed for this project involved "discharging liquid nitrogen by a wand-like device at 150 psi onto the painted outer surface."(9) It was noted in this article that "paint removal from the 11,000 sq. ft. interior takes one-third of a gallon of liquid nitrogen to remove a sq. ft. of paint in 10-15 sec."(10)

Experiments applying liquid nitrogen to rivet heads and shafts were conducted for the purpose of removing structural rivets. Several factors that are important to determine feasibility were considered. These factors include: the liquid nitrogen delivery system; the application procedure; the rivet brittle-ductile transition temperature; the time to reduce the rivet to its brittle-ductile transition temperature; the impact force required to remove a rivet; the effect that liquid nitrogen combined with the impact forces have on the girder around the hole; the effect of the condition of the rivet surface on temperature change; and the amount of liquid nitrogen needed to cool a rivet.

Abrasive Waterjet Cutting

Waterjet cutting has been around for 15-20 years and has been an accepted method for cutting material such as plastic, cardboard, and fabric. However, its cutting abilities were limited until more recently when abrasive waterjet cutting was developed. Now, the abrasive-carrying fluid has increased both the types of materials and applications for which the technique is practical.

Advantages of the abrasive waterjet cutting process are numerous. These advantages are listed below.

- **Safe**. Waterjet does not expose the base material to a flame or high temperature areas as torches do.

- **Clean**. The stream of water and grit can be easily caught and disposed of with no pollution hazard. For instance, the process generates little dust and washes away particles thereby preventing them from flying into the air.

- **No Deformation**. The force of the water and grit does not deform the cut surface of the material.

- **Quiet**. Hashish (11) states that the process is much quieter than mechanical tools and some of the other cutting operations it may replace. He notes that the noise the jet creates is actually dependent on the distance the nozzle is from the working material. The closer the nozzle to the material, the quieter the process.

- **Smooth Cutting**. Waterjets can make clean cuts on a single pass, eliminating the need for a secondary finishing operation. Hence, waterjets may be feasible to replace the reaming operation that CNR presently employs when plies are misaligned.

- **Easy Contouring.** Jets can be easily maneuvered and produce small kerfs (usually about 1/16 in.), allowing complex cuts on high strength materials.

- **No Thermal Effects.** Waterjet cutting produces no heat affected zone as occurs with laser or torch cutting. The cut stays cool, thus the mechanical properties of the material remain uniform.

- **Excellent Automation Adaptability.** Although some waterjet cutting is operated manually, most industries have switched to automated processes. Robotics have made possible the precise and accurate movement of the jet at high speeds, allowing the jet to take on jobs requiring a quality not possible with manual cutting operations.

- **High Cutting Speeds.** The water velocity exiting the waterjet nozzle is as high as Mach 3, three times the speed of sound. In 1985, Flow Systems, Inc. claimed that at 30,000 psi water pressure and 3 lb/min abrasive flow rate, waterjets can cut through 1-in. thick mild steel at a rate of 8 ipm. Now, five years later, there may be improvements in cutting rates. This has yet to be investigated.

- **Flexible Reach.** Although pumping equipment tends to be large, the cutting head in a waterjet system is small and lends itself to portable cutting operations. Due to its narrow orifice, the waterjet head is capable of reaching rivets in very small clearances.

Waterjet cutting has several advantages. It produces a clean, smooth cut with no deformation or thermal damage to the surrounding steel. Moreover, it is lightweight and easy to control. Yet, several obstacles must be overcome before adapting this method to removing structural rivets. First, waterjet cutting produces high speed water flow which may require additional safety procedures. Secondly, waterjets are most effective for cutting steel up to 1 to 1-1/2-inch thick. Beyond these thicknesses, waterjets leave jagged cuts. Third, at thicknesses greater than 2 inches, the feed rate of the jet is slow.

Presently, there are two major U.S. companies that build waterjet cutting equipment intended for manufacturing applications: Flow Systems Incorporated, Kent, WA, and McCartney Manufacturing Company, Baxter Springs, KS, a subsidiary of Ingersoll-Rand Corporation. Recently, some newer suppliers have entered the market. One is Jet Edge Corporation, a joint venture of Continental Machines, Incorporated, and Possis Corporation. A second is NLB Corporation (National Liquid Blasting).

Flow Systems calls its abrasive waterjet the Paser (particle stream erosion) system. It utilizes up to 55,000 psi of water pressure; however, cutting is usually done at about 20,000-30,000 psi. Higher pressure water cuts at a faster rate; however, requires more frequent maintenance of the nozzle orifices and, what is more costly, the intensifier seals. With a 30,000 psi water jet and abrasive flow of 3 lbs/min., Flow Systems claimed in 1985 these cutting rates:

- 1-in. thick mild steel - 8 ipm

- 1.25-in. thick stainless steel - 6 ipm
- 3-in. thick tool steel - 1.5 ipm

Ingersoll-Rand calls its system the Hydrobrassive nozzle. Its design and cutting rates are similar to that of the Paser.

The key components of an abrasive waterjet cutting system include the high pressure pump, the waterjet, the abrasive feed system, and the abrasive-jet nozzle. Secondary components include the abrasive and water catcher and accessories, such as swivels, hoses, and control valves. The high-pressure pump commonly used in the field is a 35 ksi dual intensifier pump driven by a 75 hp motor. The jet is formed with a sapphire orifice. Common diameters for cutting applications range between 0.003 and 0.020 in. "The development of catching systems to collect the abrasives and water is of prime operational importance. Typically, for field applications, a vacuum-type catcher can be adapted with a shroud surrounding the jet to catch rebounding water and abrasive."(11) Improved catching apparatuses now allow the jet to dissipate, reducing noise levels and safety hazards.

The major cost elements in the operation of abrasive waterjet systems are the capital cost of the equipment; the cost of power; the cost of abrasives; and the cost of nozzles due to wear. According to Dr. Mohammed Hashish, Senior Research Scientist, of Flow Systems Inc. in Kent, WA, the estimated hourly cost for utilizing an abrasive waterjet system is $27 U.S./hour. This cost is based on the capital cost of the equipment plus a 5 year interest of 15%, 10,000 hours of total operating time, and maintenance. "Although this may be more expensive than other cutting methods, waterjets provide smoother cuts, possibly faster cuts, minimum disturbances to adjacent structures, and is vibration-free."(12)

Powder Actuation

A tool powered by explosive cartridges remains another alternative considered for structural rivet removal. Five tool manufacturers are members of an organization called Powder Actuated Tool Manufacturers' Institute (PATMI). They manufacture tools to anchor fasteners into steel, concrete, and masonry. The "power loads" explode on the impact of a hammer or trigger device and the energy released in the explosion drives a piston that forces a fastener into the base material. The force the tool delivers is easily controlled by the make-up of the power loads which are manufactured at twelve levels for a variety of applications.

The researchers have experimented with the highest power load available to consumers - power level 4. They can ensure that with power level 4 the operator would not experience recoil, or kickback, of the tool. Although this power level is probably far below that required to remove a structural rivet, a much larger power load could be designed to accomplish the task. However, as the power load is increased, so will the recoil.

The researchers envision a tool similar to a triggered operated gun. It would house several power loads and work like an automatic rifle so that the piston could deliver repetitive impact forces, much like a pneumatic hammer. The advantages of a powder actuated tool over a pneumatic hammer are that it is lightweight and self-contained. On the other hand, because powder actuation relies on individual gunpowder cartridges, the blows per minute rate is lower than that of a pneumatic tool resulting in a slower rivet removal rate. The difference in the rates should be compared. Also, the cost of removing a rivet could be quite high if many power loads would be required.

Chisel Improvement

In August 1989 an experiment was conducted to obtain a feel for the complexity of removing structural rivets. A pneumatic hammer and air compressor were borrowed from Bethlehem Steel. The results were disappointing. The tool could not shear the rivet head off and the chisel tip proved dull and weak. In December 1989, the experiment was repeated with the same pneumatic hammer and a new and sharp chisel. The results were very similar. The chisel was capable of removing the rivet head, but at a very slow rate.

With these results in mind, the project advisory board suggested that the researchers consider adjusting the shape or material of the chisel. Perhaps a different shape or material would remove structural rivets easier. The researchers decided to experiment with various types of chisels recording any significant observations. In order to operate under conditions similar to the Canadian National Railway, a powerful class of pneumatic hammer, called a rivet buster, was required. The researchers decided to purchase this type of pneumatic tool.

EXPERIMENTATION

Physical Properties

Rivets from a bridge girder used on the Grand Narrows bridge were used for experimentation. In order to determine if the rivets were representative of those rivets that CNR will be replacing, their physical properties were determined and compared with rivets from the Queen Victoria and Beverly Viaduct bridges in Canada.

Rockwell "B" Hardness Tests

Rockwell hardness tests were performed on nine rivets from the Grand Narrows Bridge, four rivets from the Queen Victoria Bridge, and one rivet from the Beverly Viaduct Bridge. The hardness of the rivet shafts, recorded on the B-scale, ranged from B61 to B78 indicating an approximate tensile strength of 68 ksi and approximate yield strength of 43 ksi. The steel on the outer surfaces of the rivet head was notably harder, ranging from B78 to B91. Work hardening of the steel during the rivet installation process explains these higher hardness ratings.

Rivet Composition

Three rivet specimens, one representing each of the three bridges, were shipped to an independent testing facility for determination of the rivet composition. Spectrochemical analysis performed on each rivet identified the percentage of 17 elements present in the rivet material. These percentages can be seen in table I.

Table I. Spectrochemical Analysis Results on Three Sample Rivets

ELEMENT	GRAND NARROWS 1917	QUEEN VICTORIA 1896	BEVERLY VIADUCT 1908
Carbon	0.111	0.164	0.188
Manganese	0.45	0.54	0.43
Phosphorus	0.013	0.012	0.009
Sulfur	0.027	0.033	0.026
Silicon	0.01	0.06	0.08
Nickel	0.02	0.07	0.05
Chromium	0.06	0.07	0.06
Molybdenum	<0.01	<0.01	<0.01
Vanadium	0.004	0.002	<0.001
Copper	0.082	0.063	0.074
Boron	0.0007	0.0008	0.0028
Tin	0.010	0.011	0.011
Aluminum	0.011	0.009	0.004
Lead	0.024	0.024	0.018
Tungsten	0.015	0.008	<0.001
Niobium	0.01	0.01	0.01
Cobalt	0.010	0.011	0.009

The rivet steel can be classified as a low carbon steel in which carbon makes up less than 20% of the steel composition. The rivet from the Grand Narrows bridge built in 1917 contained considerably less carbon (.111) than the rivets from the Beverly Viaduct bridge built in 1908 (.188) and the Queen Victoria bridge built in 1896 (.164). The advisory board hypothesized that the lower carbon content could be attributed to the year that the Grand Narrows bridge was constructed. The year 1917 was during World War I, a time of hardship and economic depression when large amounts of steel were required for the defense industry. Such conditions may have produced materials of less quality. Yet the researchers cannot ignore the fact that rivet properties are usually classified within a broad range.

Contents of other primary elements including manganese, phosphorus, and sulfur appear to fall within the Canadian specifications.

Static Load Test

A 3-foot long section containing the bottom flange of a 6-foot deep bridge girder from the Grand Narrows bridge was cut from a larger section of girder. The smaller section was taken into the Advanced Technology for Large Structural Systems Laboratory at Lehigh University for static load tests.

A chisel tool was mounted on a 60 kip testing machine and the girder section was aligned in the machine so that the chisel tip was touching the rivet head directly against the girder. See figure 1 for alignment. An average static force of 27.4 kips was required to shear the rivet head. Once the rivet head was removed, the chisel tool was replaced by a structural steel punch approximately 1/2-inch (12.8 mm) in diameter. The girder section was aligned so that the punch would line up with the rivet shaft to back it out. See figure 2 for this alignment. The average static force required to back out a rivet shaft was 29.6 kips; yet this force ranged from 12.8 kips for the easiest case to 41.6 kips for the most difficult rivet that could be removed. Several rivets could not even be pushed out. This range demonstrates the various degrees of difficulty of backing out the rivet shafts. The higher force requirements were attributed to misaligned plates that result in a rivet with steps inside the hole.

In two cases, the plates were severely misaligned so that large increases in static force resulted in failure of the steel punch. Observations demonstrated that for these two cases, the rivet shafts did not even move.

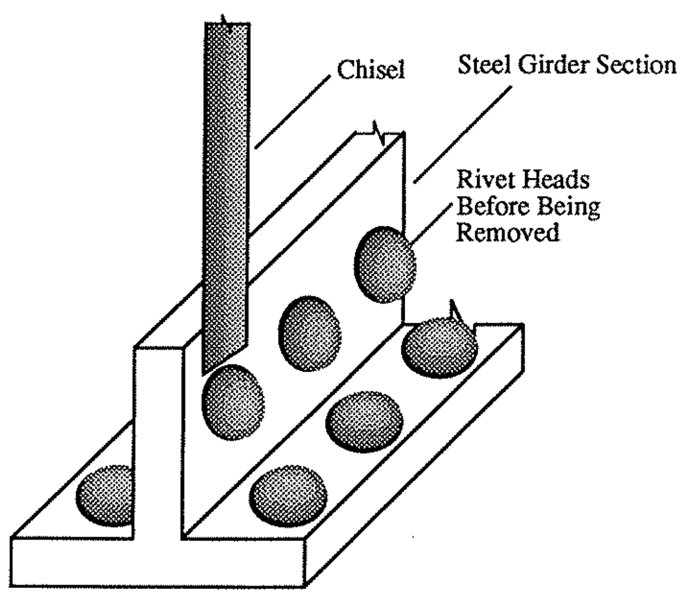


Figure 1. Chisel Alignment

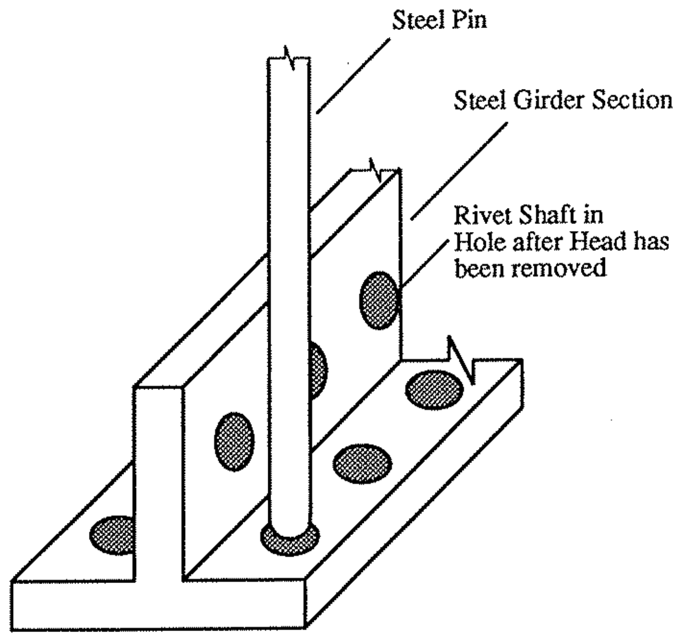


Figure 2. Punch Alignment

Charpy Impact Test

Charpy specimens were produced from the rivet shafts of those rivets from Grand Narrows and Queen Victoria bridges. The Beverly Viaduct bridge was not represented because rivet shafts obtained from the bridge were not long enough to produce Charpy specimens. Three specimens (2 from G.N. and 1 from Q.V.) were tested at five temperatures, -46^{o} (-50^{o}F), -32^{o}C (-25^{o}F), -18^{o}C (0^{o}F), -4^{o}C (25^{o}F), and 19^{o}C (66^{o}F).

The data obtained from the tests were plotted on an impact energy versus temperature graph. The graph shows a series of three "S" curves having an "upper" and "lower" shelf. Refer to figure 3. The graph shows that the brittle-ductile transition temperature of the rivet steel is in the range of -32^{o}C to -18^{o}C (-25^{o}F to 0^{o}F). Consequently, a method that could reduce the rivet temperature to -32^{o}C (-25^{o}F) should embrittle the rivet and simplify the removal process.

Liquid Nitrogen Test to Cool Rivets

Once the brittle-ductile transition temperature was identified, the next step was to determine the amount of time required to cool the rivet head-shaft interface to -32^{o}C (-25^{o}F). This is the plane on which the rivet head would shear. Another parameter required was the amount of liquid nitrogen needed to cool the rivet. The variables in this experiment were the liquid nitrogen flow rate and the condition of the rivet head: rusted, wire-brushed, and ground. The liquid nitrogen flow rate was controlled by varying the air pressure used to force the liquid nitrogen out of its storage tank and onto the rivet head. Laboratory facilities safely permitted a maximum air pressure of only 6 psi. Tests were conducted using 4 psi and 6 psi air pressures. It should be noted that a more expensive delivery system could allow the use of higher pressures.

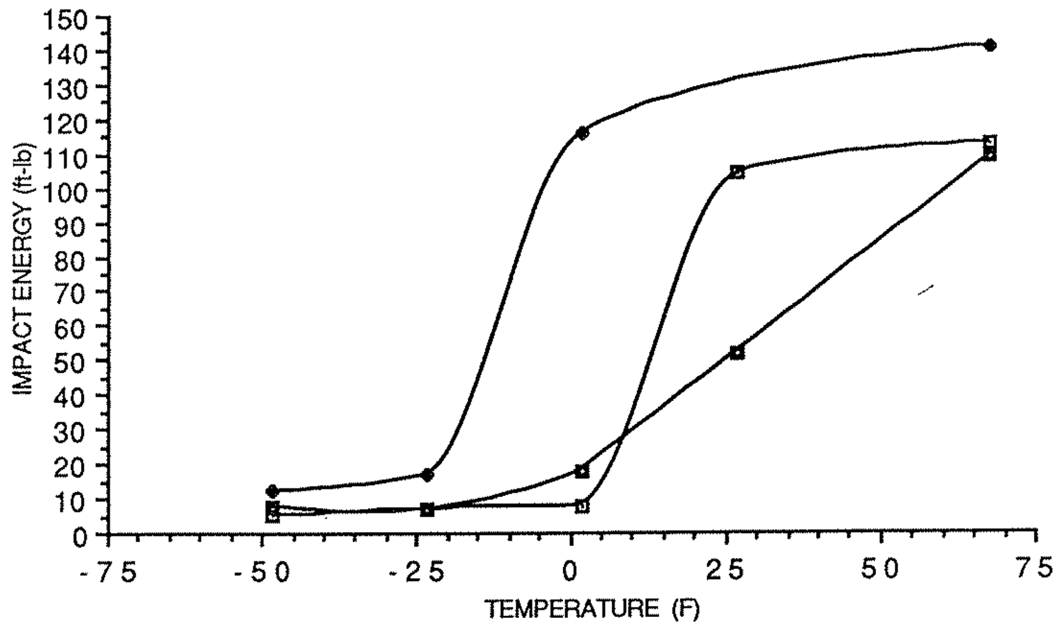


Figure 3. Ductile-Brittle Transition Temperature of Rivets

The test apparatus consisted of the sample girder section with a hole drilled down the center of the shaft. The hole was drilled from the back side so that the bottom of the hole rested on the head-shaft interface. A thermocouple was inserted into the hole and could measure the temperature at the interface. See figure 4.

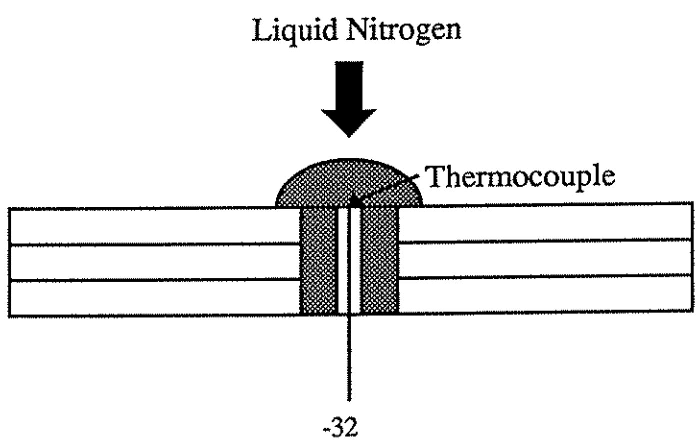


Figure 4. Thermocouple Placement on Rivet

The results are graphed in figures 5 and 6 and demonstrate that for a rusted rivet head and 6 psi pressure, 70 seconds are required to reduce the rivet temperature to -32°C (-25°F). For a ground rivet and 6 psi pressure, only 20 seconds are needed. Correlation of the data shows that for increasing air pressure (increasing liquid nitrogen flow rate), the cooling time is significantly reduced. A test utilizing a ground rivet and 8 psi pressure resulted in a significant reduction of time; only 5 seconds were required. Because temperature readings were being recorded manually, the test was over before any data were recorded. The test apparatus was such that it was difficult and unsafe to use 8 psi. Therefore, these results were not replicated. With the proper equipment, this pressure would be feasible and the time to cool would be negligible.

The weight of the liquid nitrogen used to cool one rivet head was approximated by weighing the liquid nitrogen dewar before and after application. By determining the difference, the weight of liquid nitrogen required to cool one rivet head was observed to be on average two pounds.

Removing Rivets Under Various Conditions

Several rivets were removed at room and cold temperatures using a pneumatic hammer and a variety of chisels and punches. Refer to figure 7 for a photograph. Tests were conducted to determine if liquid nitrogen significantly reduces rivet removal time. A Chicago Pneumatic 80 was purchased from Michigan Air Tools and used to remove the rivets. The air hose carried 78-90 psi pressure. Five chisels and three punches were also purchased from the same manufacturer. Rivets were removed at room and cold temperatures using different tools and their respective removal times were recorded. The hammer, tool, and operator descriptions are found in table II. The Rockwell "C" hardness of the chisels and punches are listed in table III. Finally, the chisels and punches with their corresponding identification numbers are photographed in figure 8.

The rivet head removal times for some of the tools at room and cold temperatures are compared in figure 9. Unfortunately, there was no significant reduction time in rivet head removal noted. The rivet heads were cooled by the liquid nitrogen application system described in the liquid nitrogen tests. Air pressure at 6 psi to control the liquid nitrogen flow rate was used. Tests indicated that at 6 psi, the time required to cool the rusted rivet head to its brittle temperature was approximately 55 seconds. To allow for heat gain in the rivet during the time it takes to remove the liquid nitrogen application system and begin hammering as well as the heat gain during the first couple of impact blows, the rivets were cooled for 120 seconds. Once the rivet head was removed it was noted that the shearing surface was warm. The procedure the researchers used was insufficient in keeping the rivet below the transition temperature.

Another attempt was made to cool the rivet for 120 seconds before impact and then during the impact. Once again the shear surface was warm.

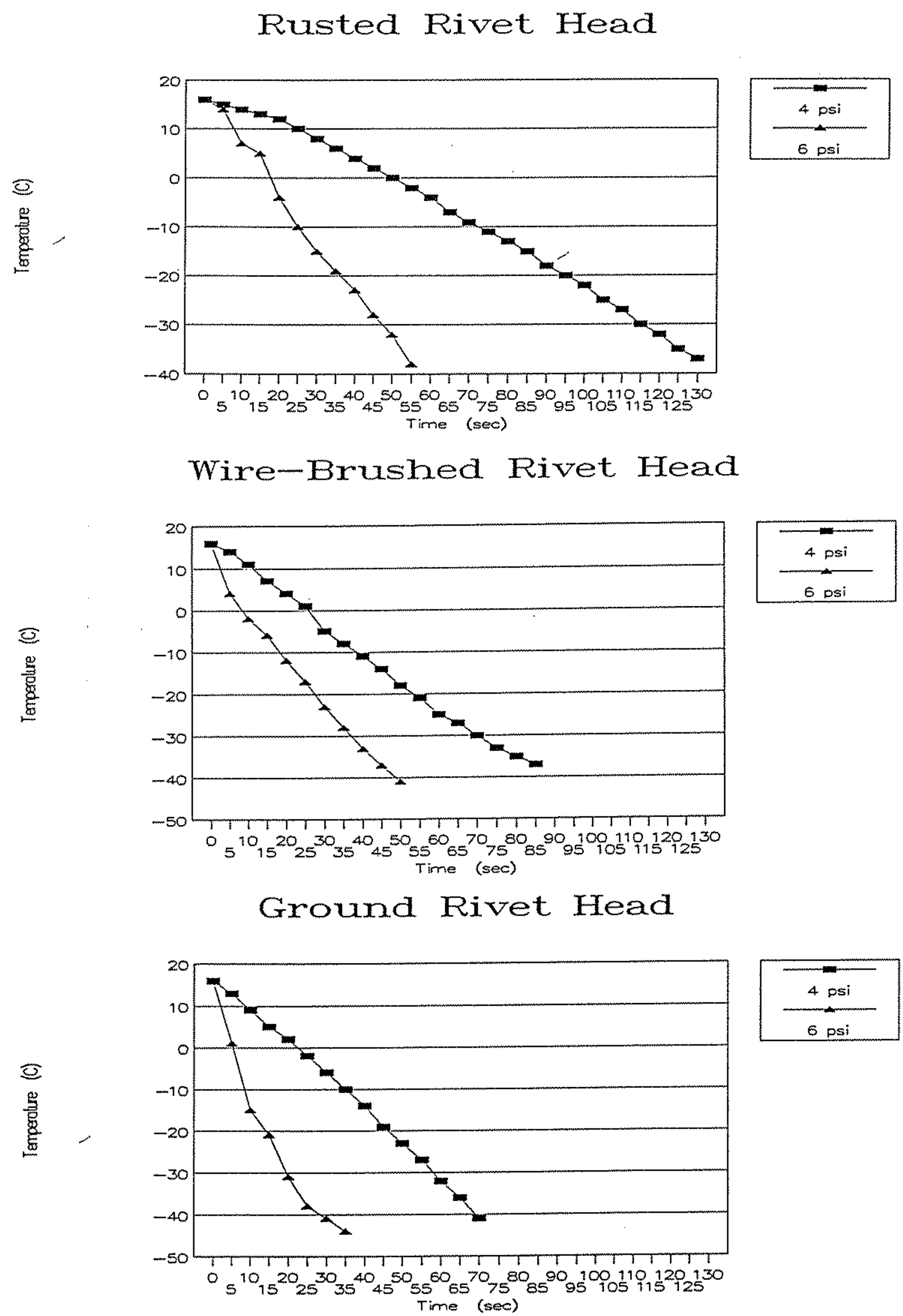
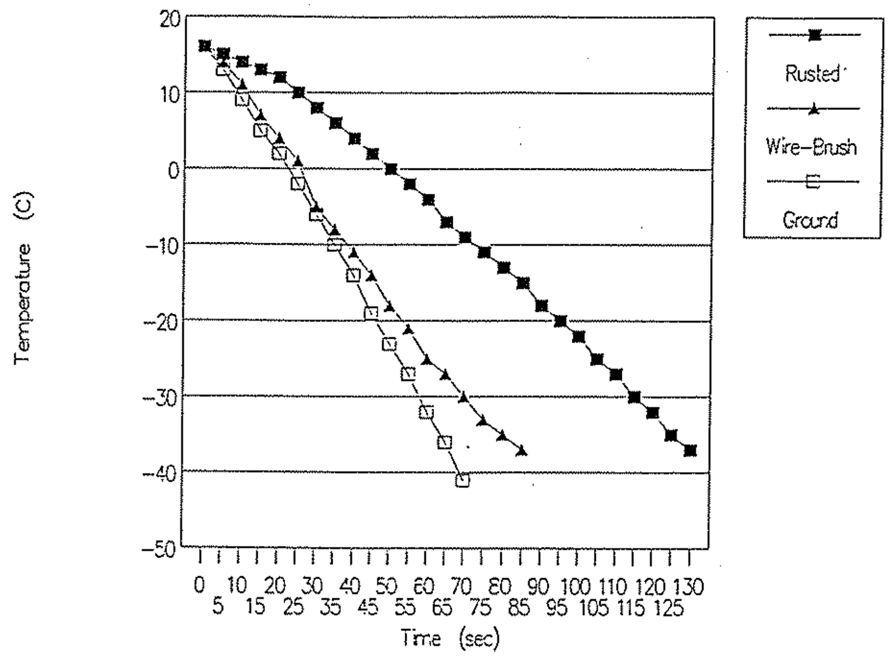


Figure 5. Influence of Rivet Head Condition on Cooling Time

Air Pressure = 4 psi



Air Pressure = 6 psi

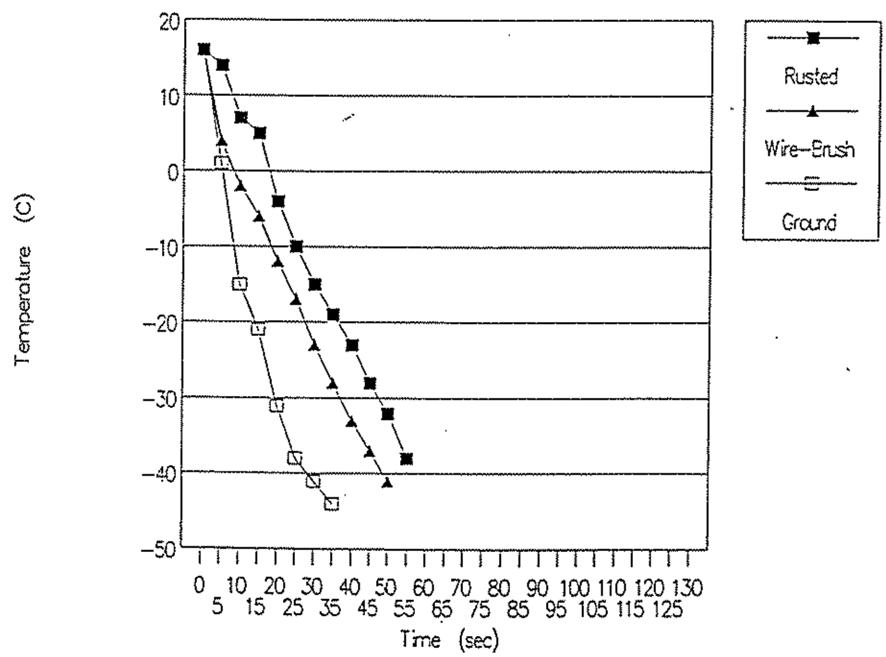


Figure 6. Influence of Air Pressure on Cooling Time

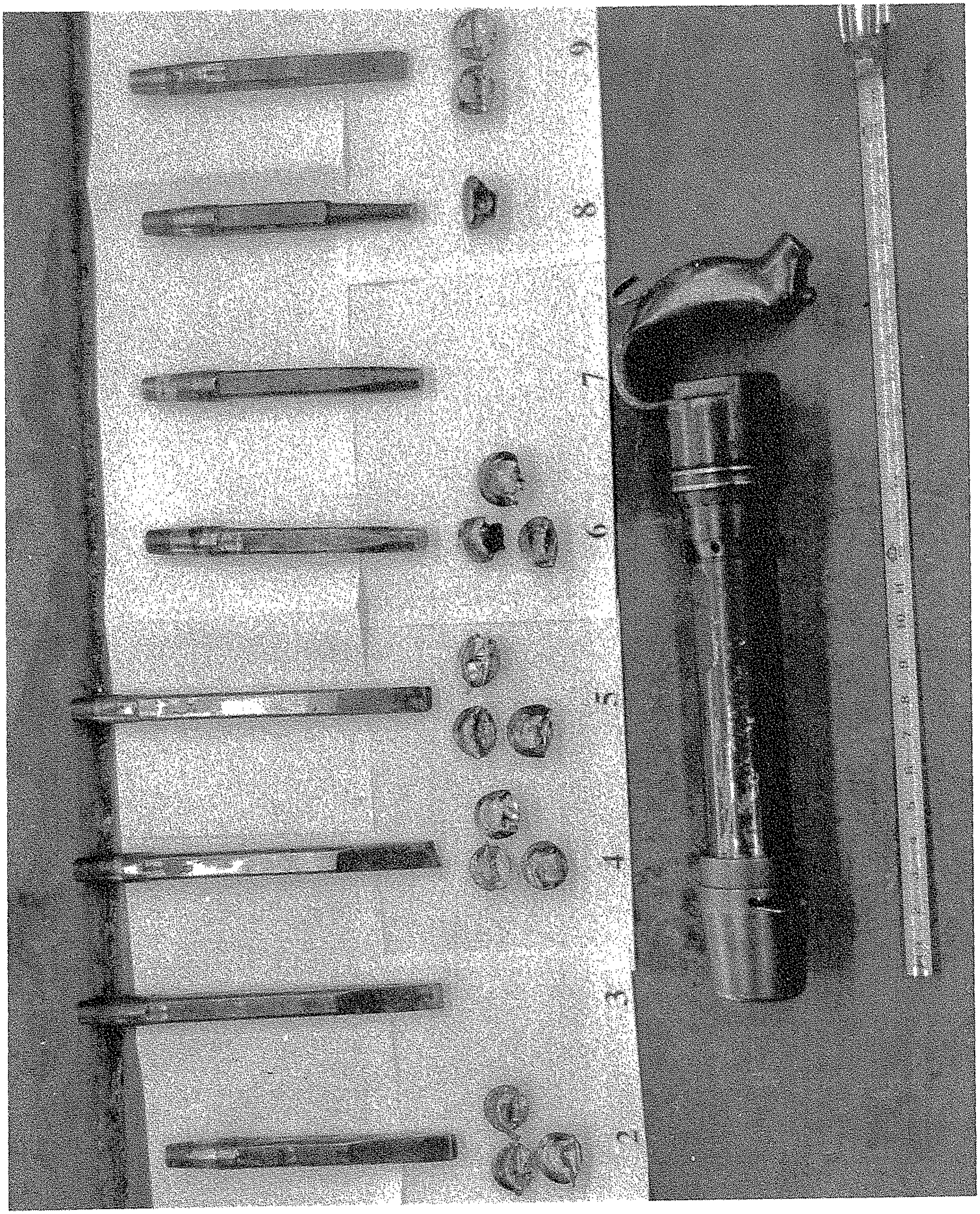


Figure 7. Chicago Pneumatic 80 with Chisels and Punches

Table II. Pneumatic Hammer Specifications and Tool and Operator Information

RIVET REMOVAL TESTS WITH MICHIGAN PNEUMATIC HAMMER, CHISELS, AND PUNCHES

Tool Specifications CHICAGO PNEUMATIC 80	
capacity:	1-1/8" rivets
bore:	1-1/16"
piston stroke:	9-1/2"
blows per minute:	1200
length:	22"
weight:	24 lbs.
shank diameter:	1.217"
air inlet thread:	3/8"

Operator Information

Man	Weight	Height
Dave	230 lbs	6'-1"
Todd	160 lbs	5'-10"
Bob	150 lbs	5'-10"
Mike	140 lbs	5'-10"

Chisel Information

No.	Description
1	9" Dull Standard
2	9" Sharp Standard
3	12" Sharp Standard
4	12" Dull Standard
5	12" Sharp Standard
9	9" Side Cut (old #1)

Punch Information

No.	Description
6	3/4" x 6"
7	3/4" x 6"
8	1/2" x 6"

Table III. Rockwell "C" Hardness of Tools

Tool Information No.	Description	Average Rockwell "C" Hardness	Tensile Str (ksi)
1	9" Dull Standard	51.2	266
2	9" Sharp Standard	50.4	255
3	12" Sharp Standard	54	292
4	12" Dull Standard	53.3	285
5	12" Sharp Standard	54	292
9	9" Side Cut (old #1)	--	--
6	3/4" x 6"	51.8	272
7	3/4" x 6"	49.8	253
8	1/2" x 6"	52.1	266

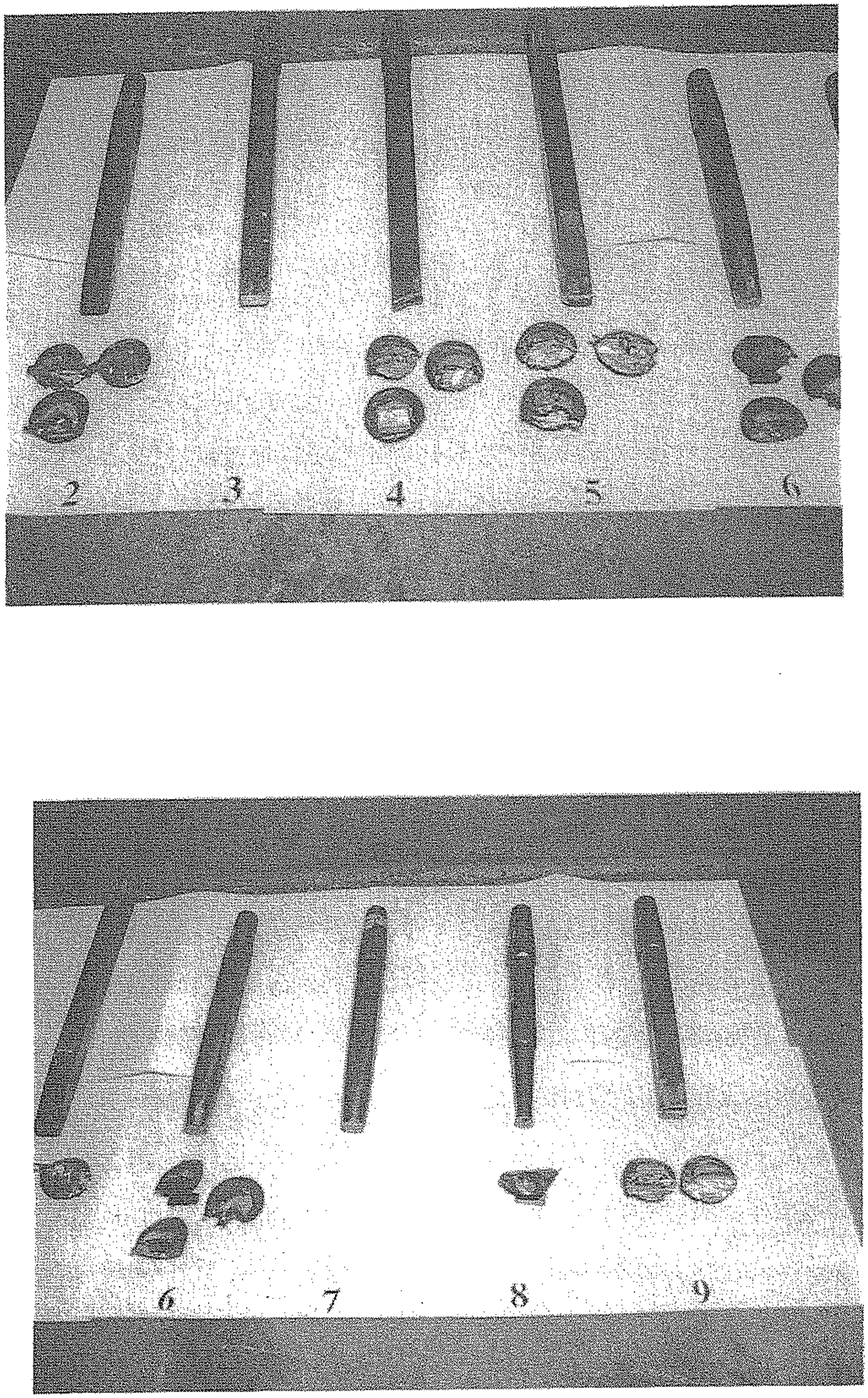


Figure 8. Chisels and Punches with Their ID Number
and the Rivet Heads Each Removed

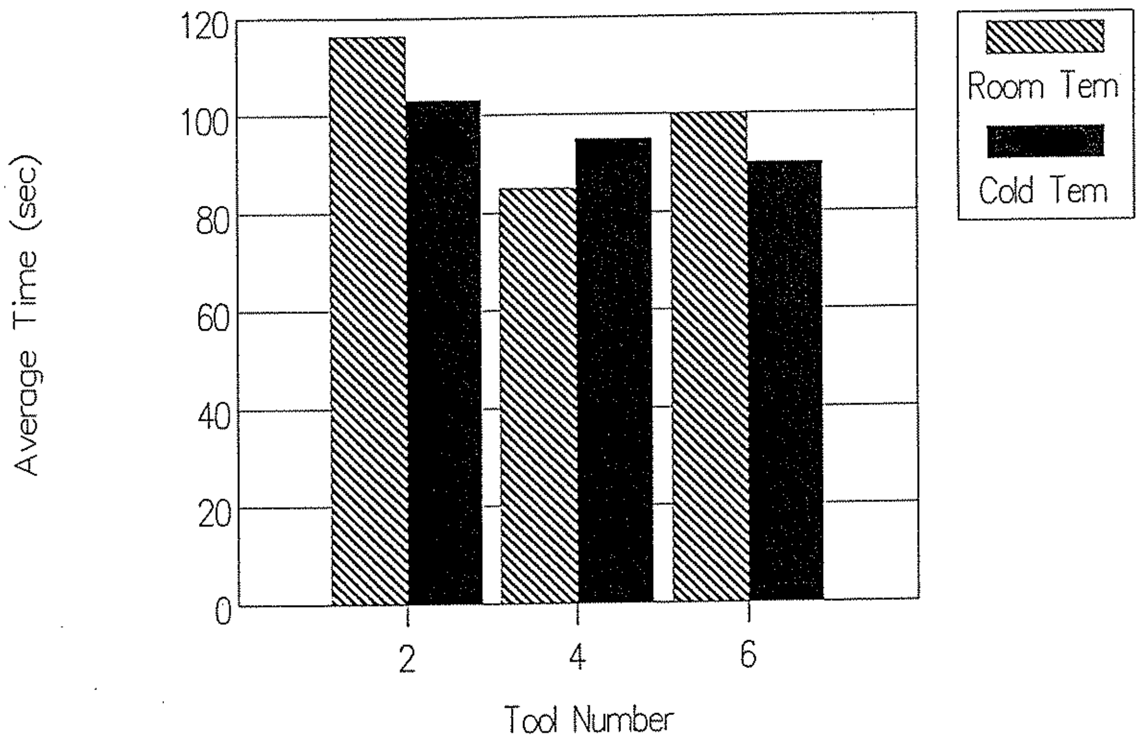


Figure 9. Comparison of Tools and Their Removal Times at Room and Cold Temperatures

Seven rivet shafts, 1-1/2 inch long, were backed out, five at room temperature and two at cold temperature. The removal times were 10-20 seconds and no significant reduction in removal time at cold temperature was noted. Of the seven, two shafts could not be removed. A photograph of a removed shaft with a clean hole can be found in figure 10.

Both the chisels and steel punches were used to remove the rivet heads. As one reviews the experimental data, it can be observed that the punches seemed to remove the head quicker than the chisels at both room and cold temperatures. More trials were performed at room temperature. The rivet head removal times for the tools at room temperature are compared in figure 11. A photograph of the chisels and punches with the rivet heads each tool removed can be found once again in figure 8, while photographs of the removed rivet head with the clean hole can be found in figures 10, 13, and 14. A sketch showing the use of a punch to remove a rivet head is shown in figure 12.

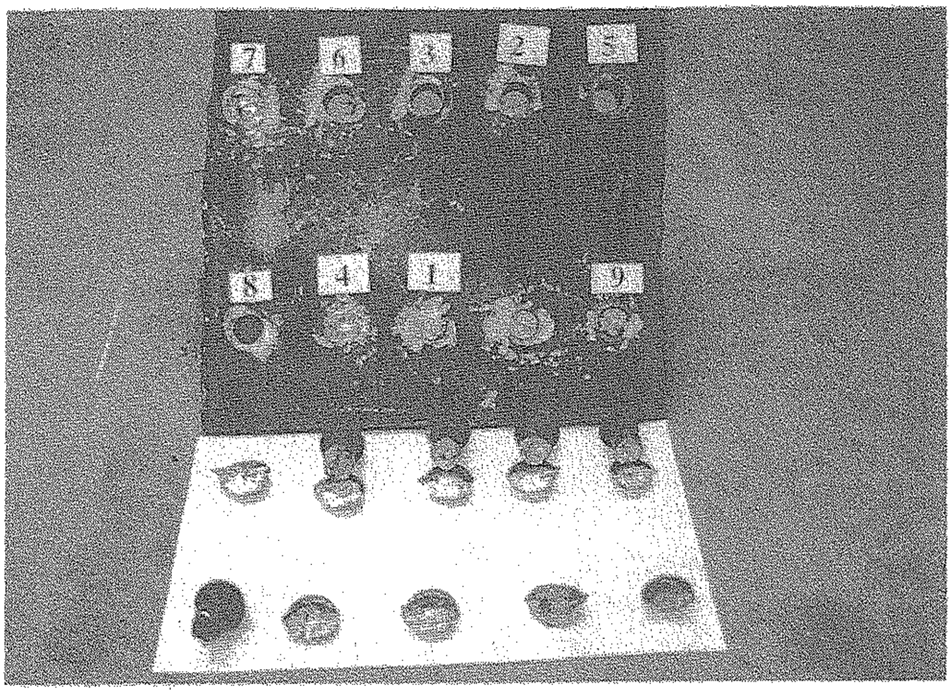


Figure 10. Removed Rivet Shafts and Rivet Heads Next to the Clean Hole

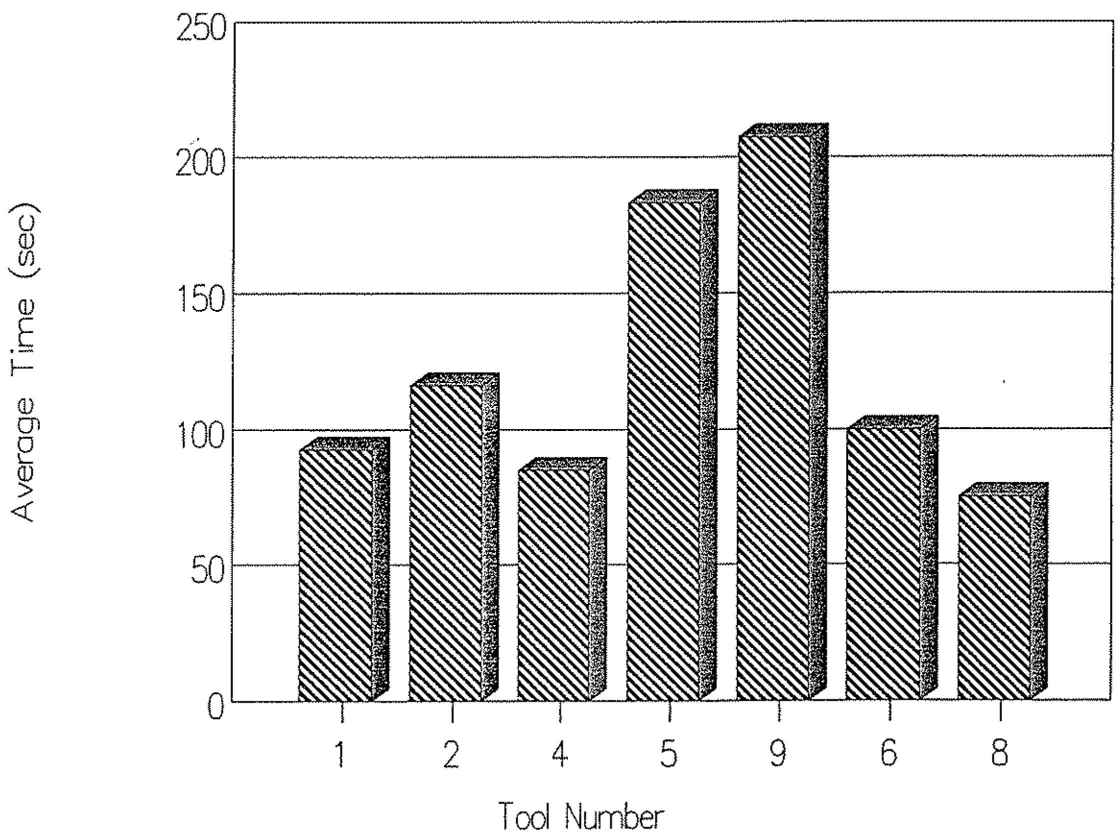


Figure 11. Comparison of Tools and Their Removal Times at Room Temperature

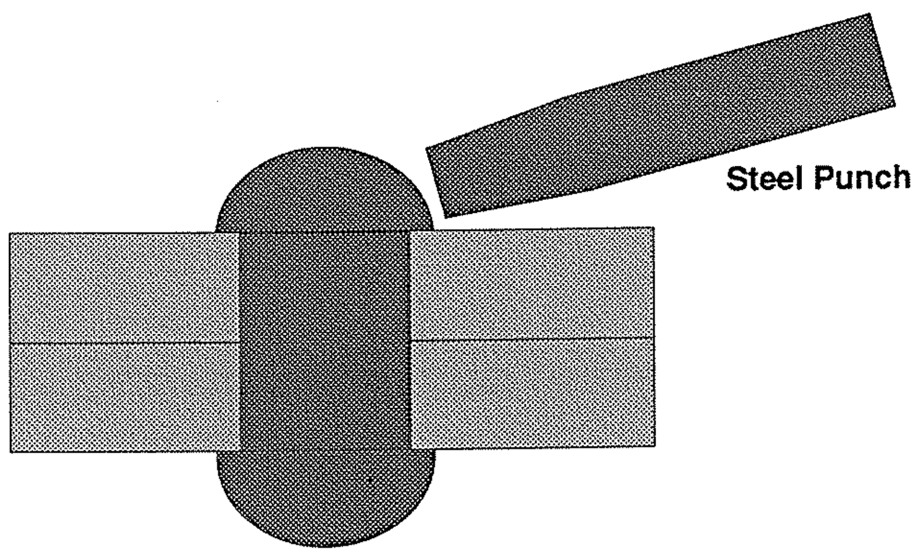


Figure 12. Rivet Head Removal With a Punch

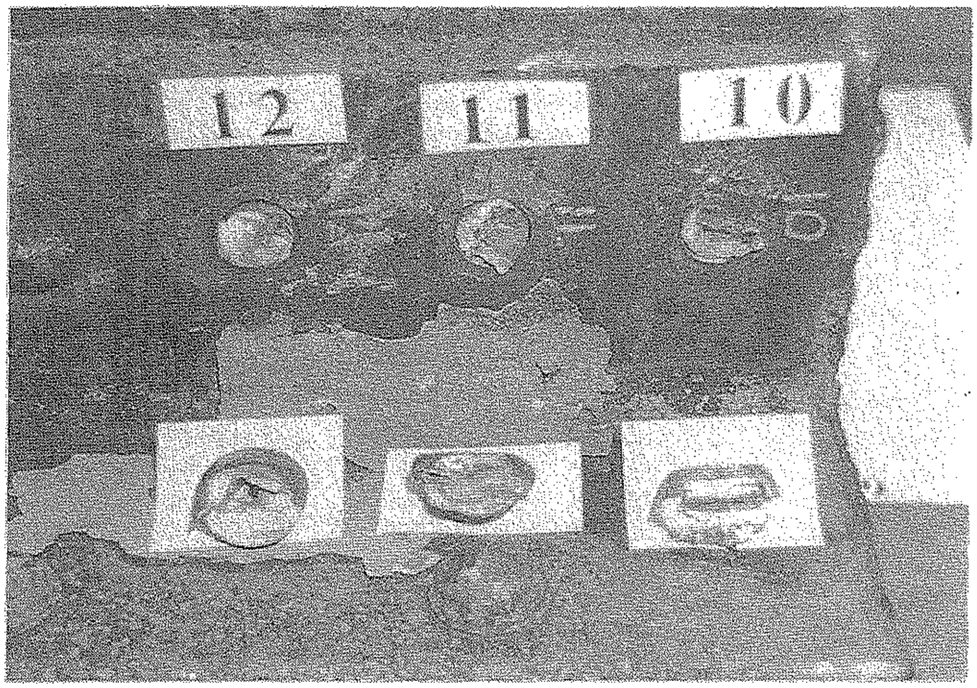


Figure 13. Removed Rivet Heads Next to Their Clean Holes

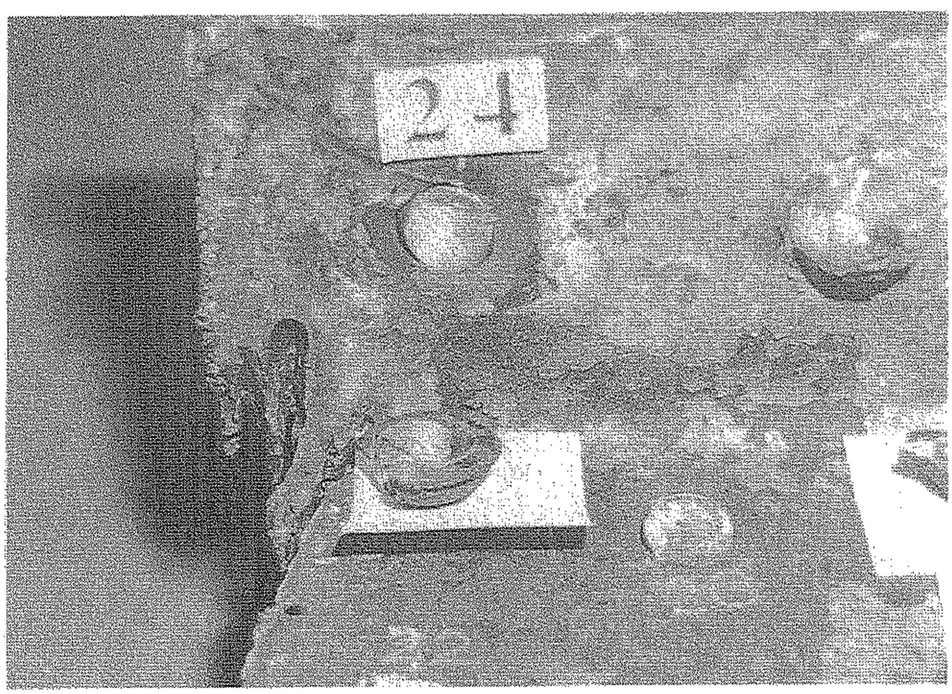


Figure 14. Removed Rivet Heads Next to Their Clean Holes

Abrasive Waterjet Cutting Tests

A sample piece of girder with several rivets was taken to Laser Applications, Inc. (LAI), a company in Westminster, MD, that specializes in laser and waterjet cutting. The waterjet supply system was manufactured by Ingersoll-Rand and the positioning table was computer controlled by an Allen-Bradley controller. Because of the large number of variables that must be specified, it was decided that the objective for these tests was not to find the optimal conditions. Instead, many different types of cuts were attempted to demonstrate the capabilities of the process.

The primary variables which were manipulated were grit size, orifice and nozzle size, and feed rate. Initially cutting was performed with 120 grit garnet. Later, 80 and 50 grit garnet were used. The grit size corresponds to that of typical sandpaper, with a smaller number indicating a coarser grit. The nozzle and orifice sizes were chosen based on the size of the grit. A bigger diameter nozzle and orifice were used with the heavier grit. The experimental data can be seen in table IV.

Table IV. Experimental Data from Waterjet Cutting Experiments

#	Grit	Orifice (in)	Nozzle (in)	Thickness (Ply)	Speed (ipm)	Comment
1	120	0.009	0.035	2	.6	
2	120	0.009	0.035	NA	1.4	Cut off head
3	120	0.009	0.035	3	.3	Blow through at 2 minutes
4	120	0.013	0.048	2 + heads	.8	7/8 hole through both rivet heads
5	120	0.013	0.048	2 + heads	1	1" hole through both heads
6	120	0.013	0.048	2 + heads	.2	very slow to contrast finish
7	120	0.013	0.048	2	<.3	Copper slag abrasive (poor)
8	80	0.013	0.048	2	2.4	Blow through 30 seconds
9	80	0.013	0.048	4	1	ragged edge
10	50	0.013	0.048	4	1.2	drill through 3 1/2 minutes
11	50	0.013	0.048	4	1.0	drill through 1 1/2 minutes upside down from trial #10
12	50	0.013	0.048	2	2.5	hole in girder
13	50	0.013	0.048	2	1.3	1.5 inch hole around heads

Several different types of cuts, see figure 15, were performed to simulate various methods of removal. Figure 15a shows the method of removing a rivet which does not have a head. The machine was set up to drill a hole through the center of the shaft, slowly cut to the outside radius, and finally cut around the circumference. The first trial, labelled as hole #1 in figure 16, cut a 7/8 inch diameter hole. This left a small portion of rivet shank intact. While at LAI, no explanation could be found for the remaining material. However, after returning to Lehigh and studying the specifications, it was found that the holes in the plates were originally 15/16 inch diameter. When the 7/8 inch diameter rivet was installed, it would deform to the dimension of the plates and thus have a 15/16 inch diameter shank.

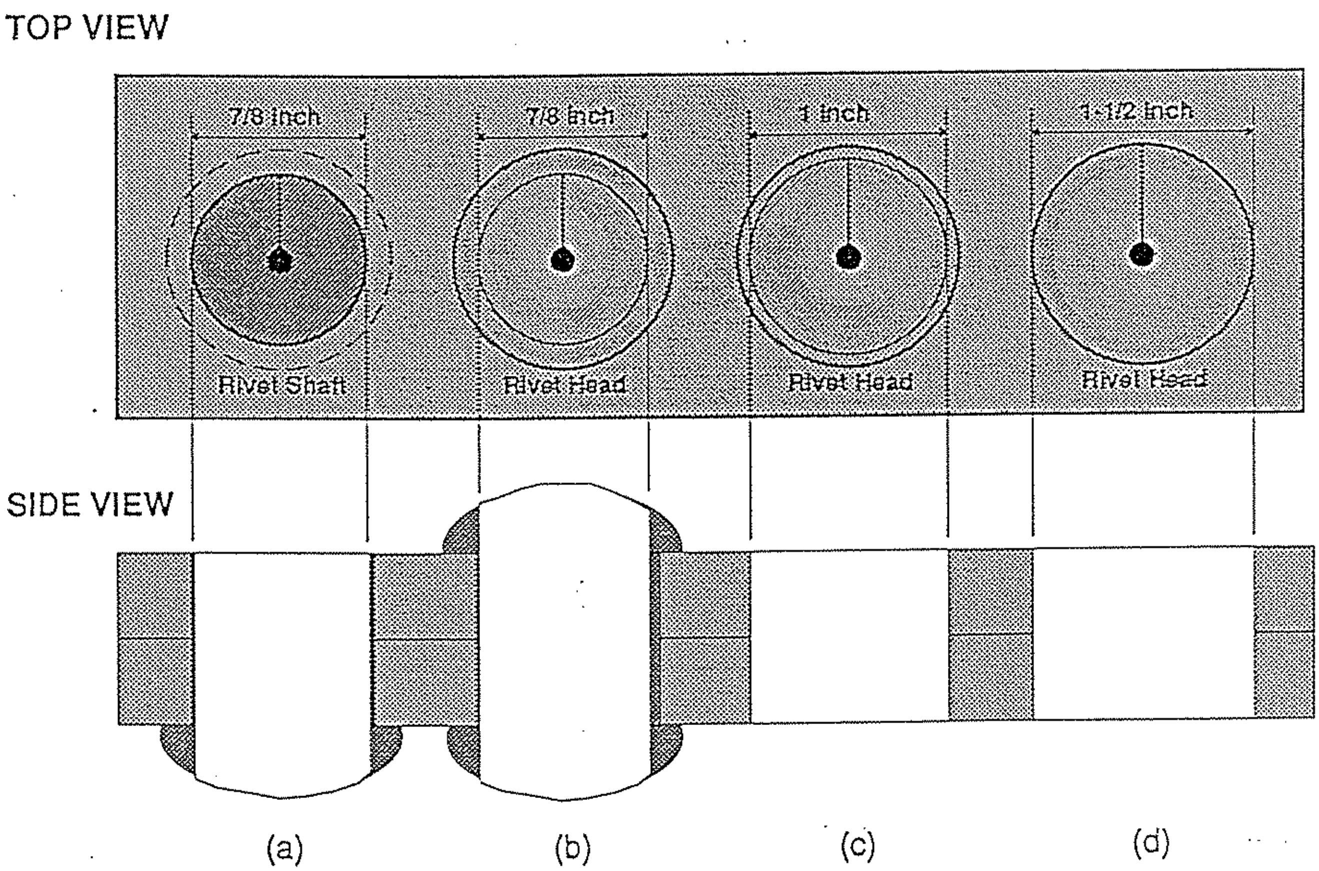
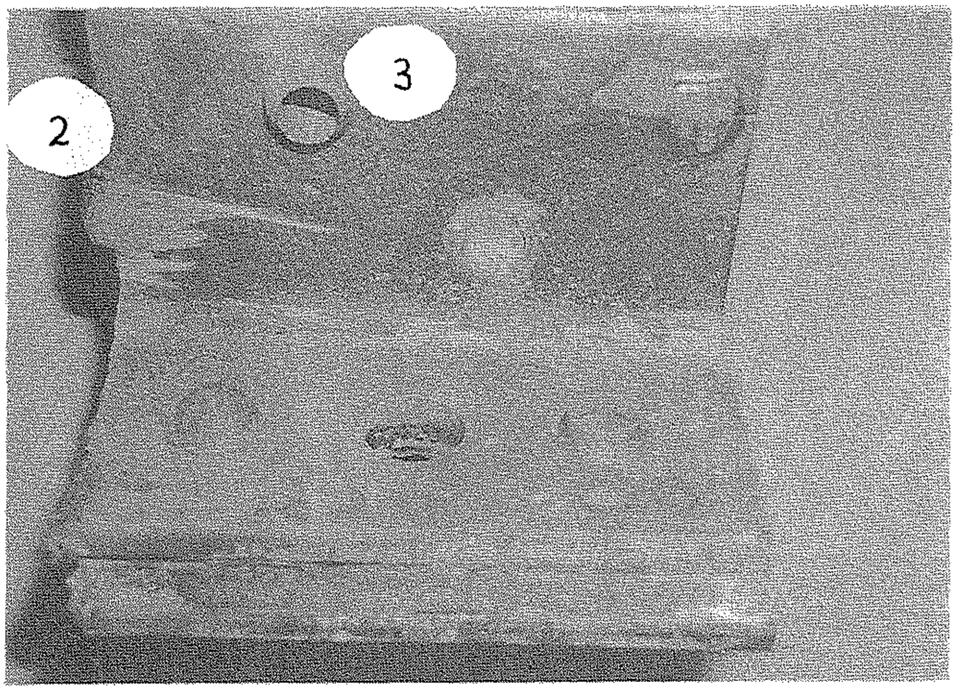


Figure 15. Sample Cuts Using an Abrasive Waterjet

The second trial was to attempt removal of a rivet with both heads intact. In this case, shown in figure 15b, a 7/8 inch diameter hole was cut concentric with the outside of the rivet head. The theory behind this trial was that the rivet head would not have to be removed first and thus time could be saved. However, since the hole was slightly smaller than and not perfectly concentric with the rivet shaft, the remaining material from both the heads stayed tightly attached to the shaft. A blow from a large hammer might remove the heads. One can see the resulting material in holes 3, 4, and 6 on the girder photographed in figure 16.



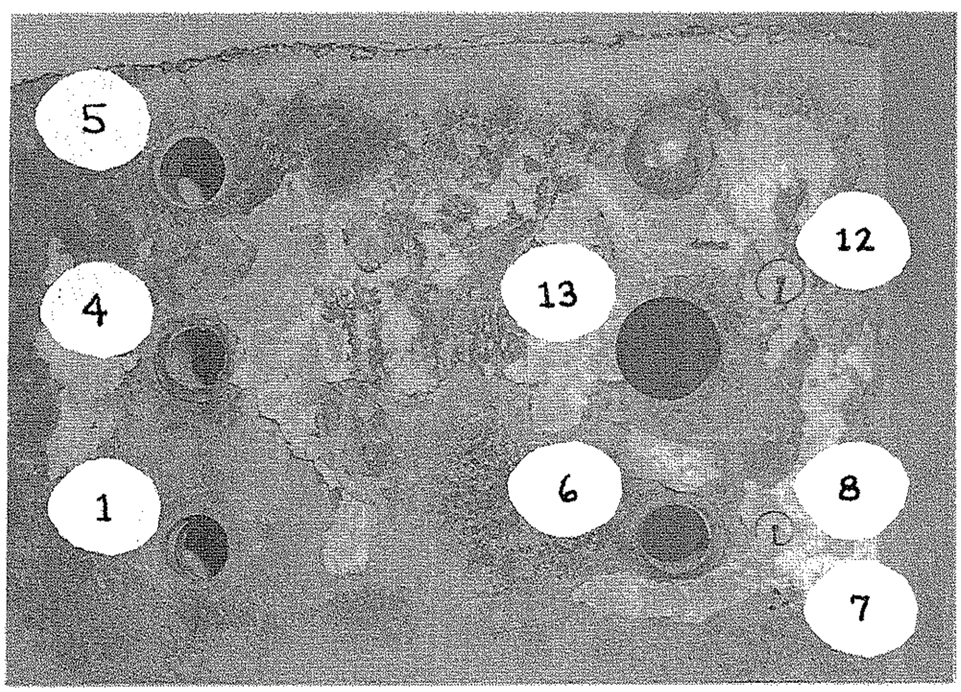


Figure 16. Waterjet Cutting Experiments on a Girder Section

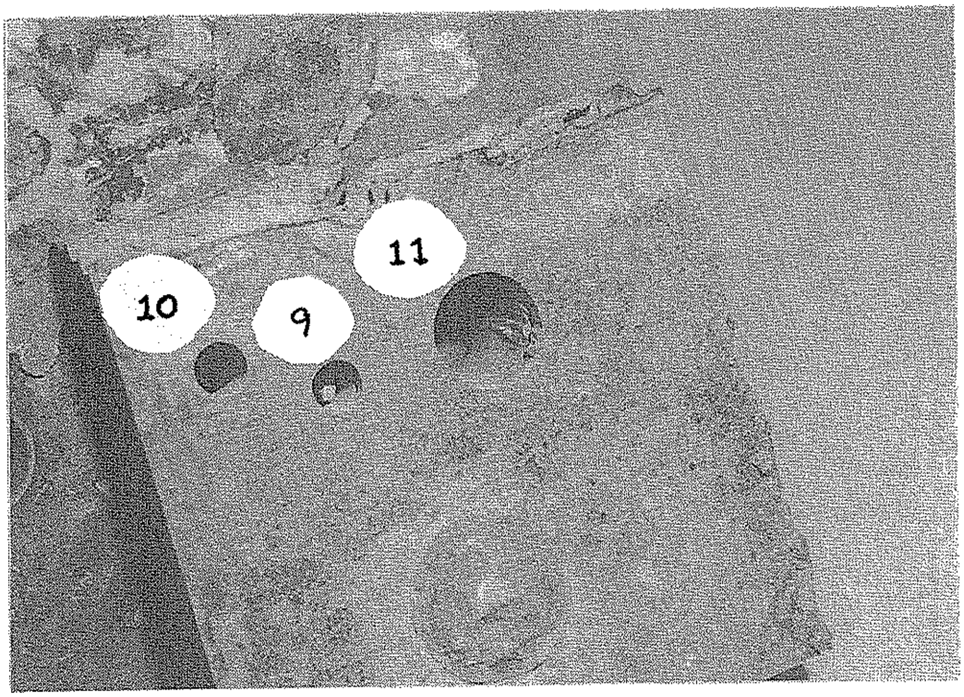
The third trial was an attempt to remedy the alignment problems of the second trial. In this case a 1 inch diameter hole was cut in the center of the head as shown in figure 15c. This would allow for some misalignment between the shaft and head of the rivet. No trials were performed using 15/16 diameter holes. Just as in the second trial, both heads remained attached. However, in this case there was only a small amount of material holding the head to the shaft. In fact, a small hammer was used to knock the head loose. The cut left a 1 inch diameter hole in the girder which can be seen in at hole 5 in figure 16. Further tests need to be conducted to determine if the heads could be consistently removed with little or no force. Further analysis must be performed to see if a 1 inch hole creates problems for a 7/8 inch bolt. If this is a problem, the possibility exists to use a slightly larger bolt.

A significant portion of the time to remove a rivet using this method is the time to drill through the rivet. By requiring the jet to penetrate both heads, an additional 3/8 inch to 3/4 inch of material must be drilled. Similarly, a slower feed rate must be used to allow the jet to cut through the thicker material around the circumference. For this reason the fourth trial was performed by cutting around the entire rivet head. This created a 1-1/2 inch diameter hole as shown in figure 15d and can be seen as hole 13 in figure 16. It is hypothesized that the use of 1-3/8 or 1-1/2 inch bolts could cause additional problems and increase costs. Nevertheless, the test was performed to compare the difference in cutting time.

The limit of material thickness in all tests was approximately 2 inches. Beyond this thickness the edges of the holes became ragged and larger in diameter. One solution to the problem of a larger diameter hole on the bottom plate would be to slightly angle the gun inward. Since all of the holes are the same diameter, a standard tool could be developed with the proper angle based on the joint thickness.

The time to cut around the circumference of a two inch thick plate would be approximately 5 minutes. For thinner plates the time would decrease proportionally. By performing more trials, there is a possibility of finding better values for the parameters and thus, reducing this time. However, it is doubtful that more than 10% improvement could be expected with the current technology.

An attempt to better determine the cutting surface of material thickness larger than 2 inches was made. The water jet cut a hole in a small girder section containing four connecting plates. This girder section is photographed in figure 17. The plates varied in thicknesses from thinnest on the "top" to thickest on the "bottom." In addition, a gap existed between the thinnest and next thinnest plates. When the water jet cut from the thinnest plate first through the thickest plate last, a hole took significantly more time to complete than when the water jet cut from the thickest plate first through the thinnest plate last. The advisory board concluded that the reason for this time difference was primarily due to the location of the gap. The gap caused the water stream to disperse. When the gap occurred closer to the water jet nozzle (at hole 10), the water stream dispersed earlier than when the gap was further away from the water jet nozzle (at hole 11). This early dispersement resulted in lower water stream cutting power before cutting through the two thicker plates. When the water stream cut from the thickest plate to the thinner, the gap occurred closer to the bottom of the cut thereby dispersing the water stream before having to cut through only the thinnest plate. Obviously, this approach took less time. A separate photograph of the plugs in figure 18 demonstrates that the cut is less jagged for when the water stream had cut from the thickest to the thinnest plate (plug 11) and therefore verifying that the stream did not disperse until near the bottom of the cut where the gap occurred.



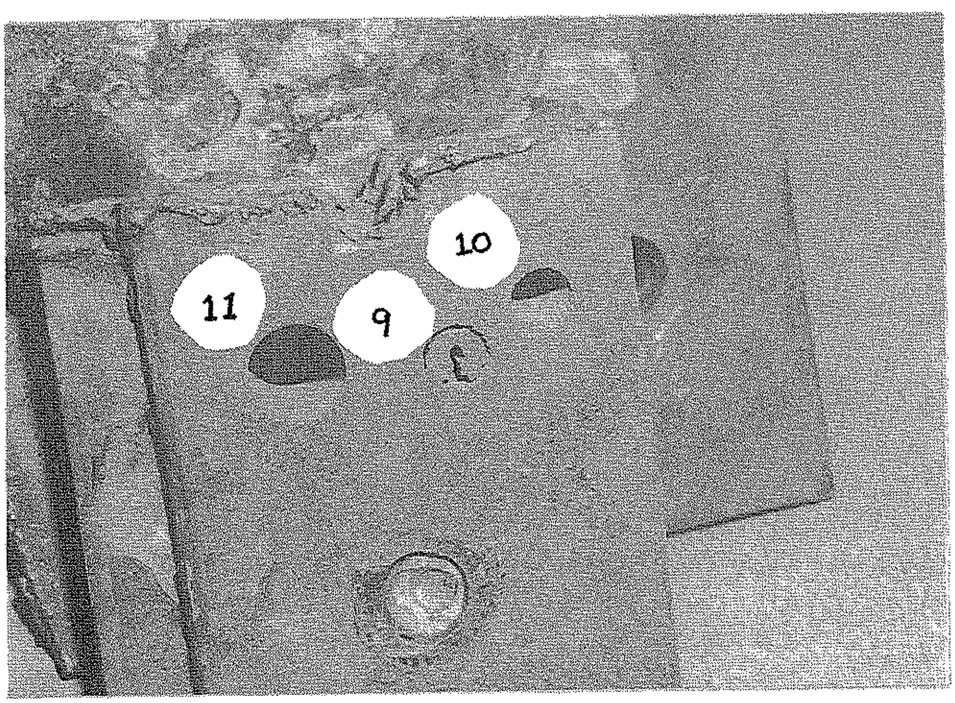


Figure 17. Waterjet Cutting Experiments on Four Connecting Plates

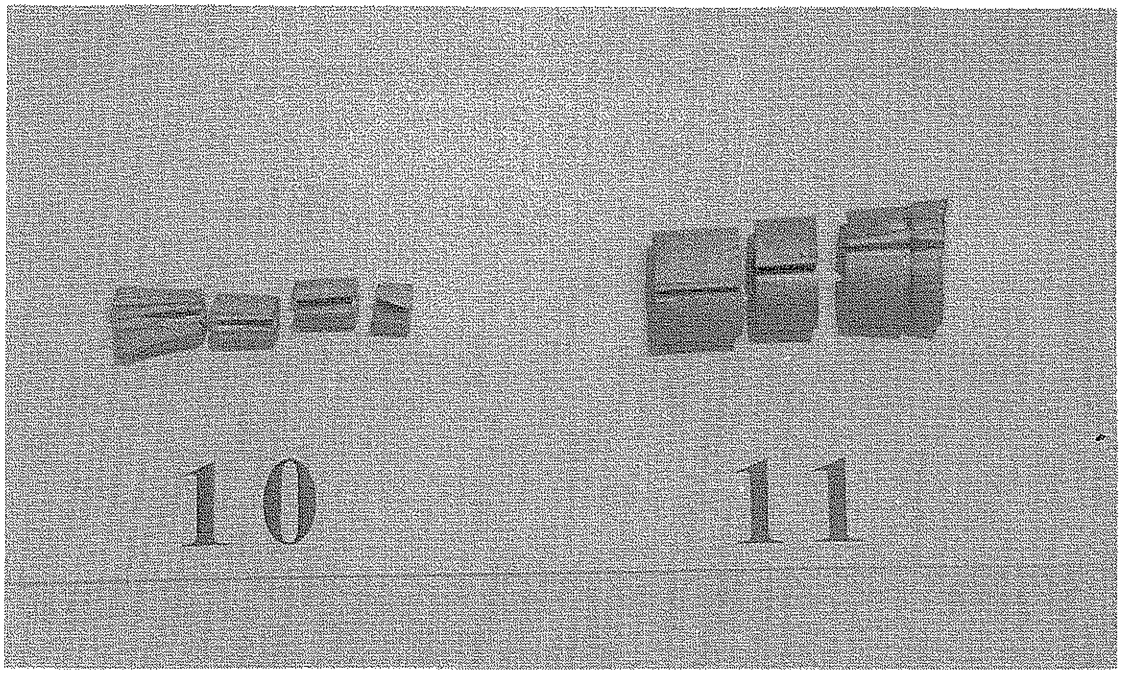


Figure 18. Waterjet Cutting Plugs from the Four Connecting Plates

Another trial attempted to remove a rivet head using a waterjet. For this trial, an "easy" rivet along the edge was chosen. The nozzle was positioned so that it was parallel with the plates holding the rivet. Refer to #2 in the photograph in figure 16 and notice minor damage to the face of the top plate. The damage occurred when the nozzle was delayed for 25 seconds. This delay would not occur in a program tuned to this task. This rivet head was removed successfully in approximately 60 seconds, less time than using a pneumatic gun. However, it was a rivet close to the edge of an open corner. It is difficult to imagine how a tool could be designed to remove the head on a web to flange joint. In any case, this option should be explored.

All of the plugs that were cut out of the girder during the waterjet cutting experiments are photographed in figure 19. In figure 20, a separate photograph of plugs 5 and 6 is shown. Plugs 5 and 6 are the same diameter cut from the same girder. The only difference was the cutting speed, which was 1 ipm for plug 5 and 0.2 ipm for plug 6. Plug 6, as a result of slower cutting speed, shows no jagged edges compared to plug 5. Therefore, in order to reduce jagged edges in thicker materials, the cutting speed could be adjusted.

It should be noted, however, that the times listed in these tests could effectively be cut in half by operating two tools simultaneously. Since two men are no longer required to hold the tool and since during the cutting time the operator is idle, he could set up one nozzle while the other is cutting. Two or sometimes three nozzles can be operated from the same waterjet supply system so the additional cost would be minimal.

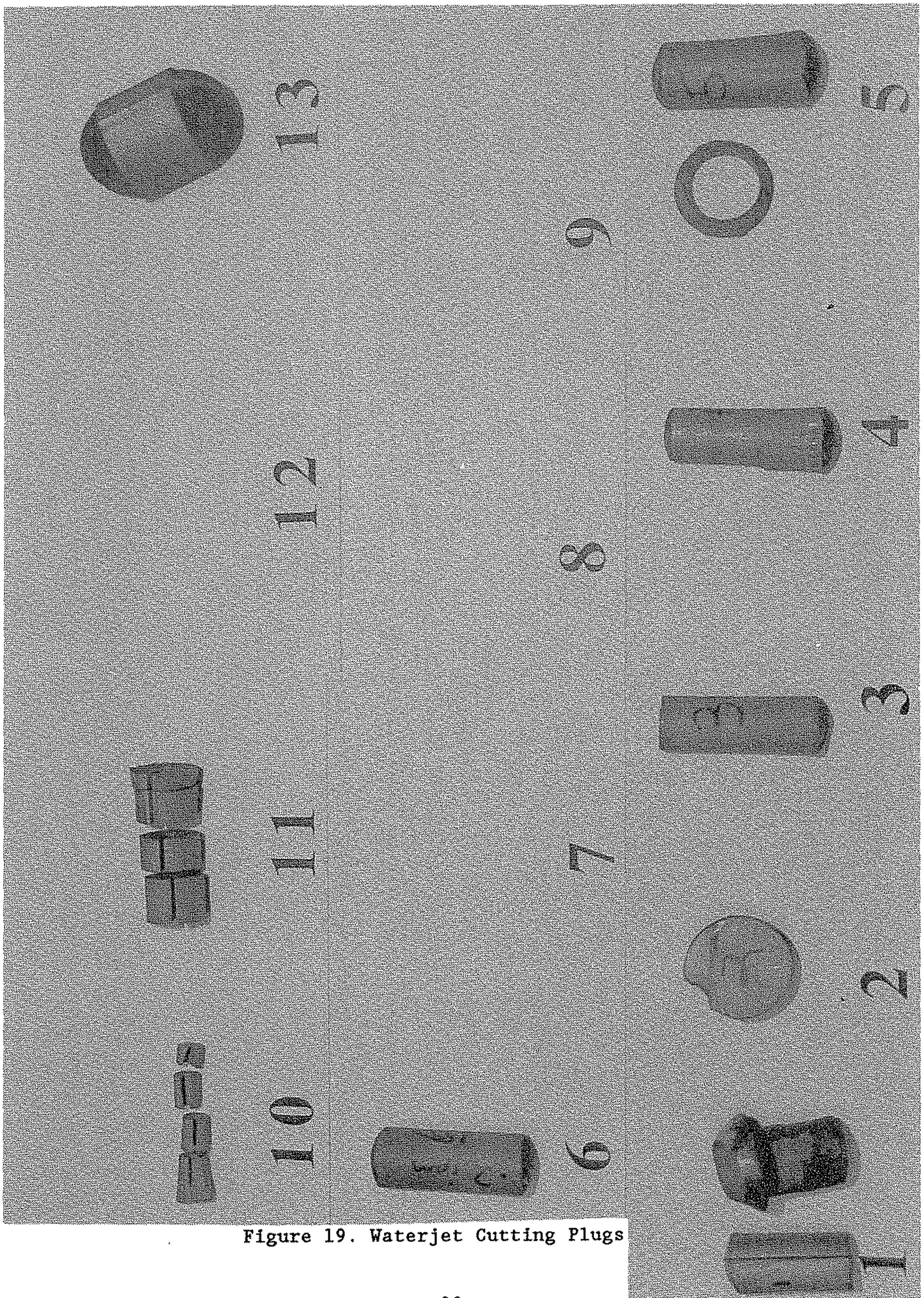


Figure 19. Waterjet Cutting Plugs

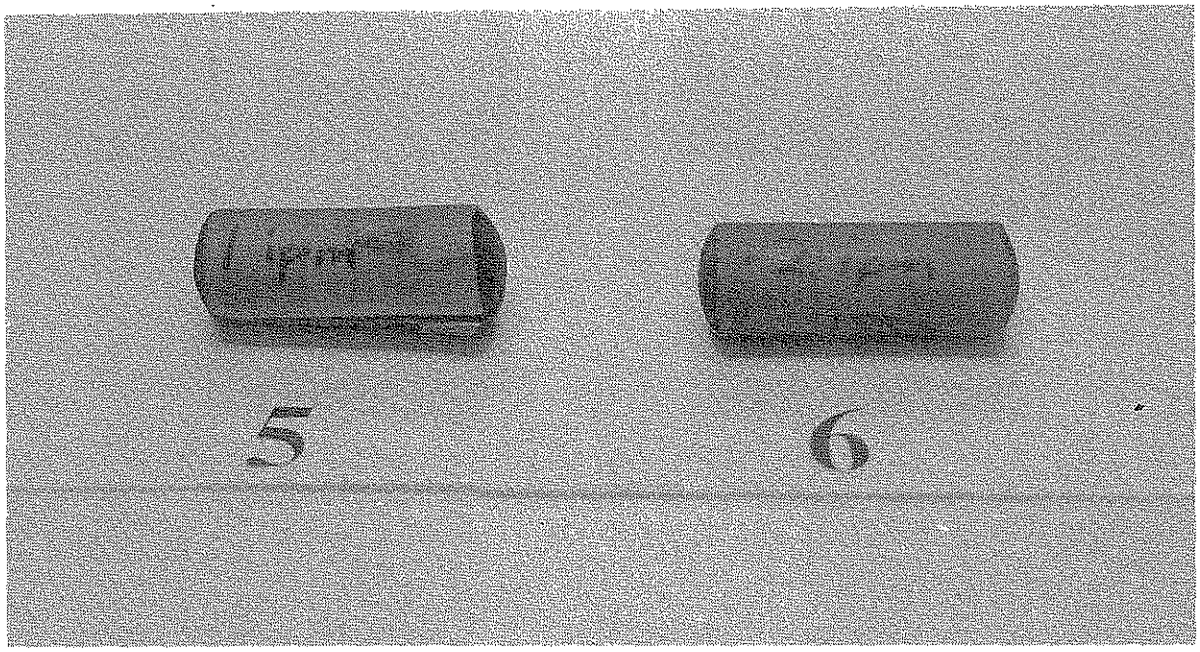


Figure 20. 1 ipm vs. .2 ipm Waterjet Cutting Speeds

The president of Laser Applications, Inc. was interested in the this application and indicated that they would be willing to work with the research team to develop any tools or methods required. He believes that the abrasive waterjet process will see substantial improvements in the next 3 to 5 years. He was enthusiastic about the potential of new waterjet systems with higher pressures and abrasives that are being developed. For example, there has been a tremendous improvement in nozzles in the past year. Previously they could cut for only one or two hours with a nozzle. Now, a nozzle lasts for more than a week.

The cost of the garnet abrasive varies from \$0.15/lb to \$0.50/lb (US). To get an accurate estimate of total cost, one must factor in the shipping charges. Often these are higher than the cost of the abrasive. The rate of consumption during cutting is normally between 3/4 and 1 lb per minute. The actual weight used in these tests was not measured.

In the area of safety issues, the research team believes the process would be easier to adapt than first estimated. While the jet is hazardous to humans for 20 or more feet, few precautions would be required to protect the girders behind the rivet being cut. As the stream exits the item being cut, it is dispersed. In one of the trials, the girder was placed on a piece of aluminum. The aluminum backing was about 6 inches beyond the exit point of the stream from the girder. Even with a 25 second dwell, there were no marks left on the aluminum backing. With an undiverted stream of water, if the nozzle to work distance is more than a foot or two, the nozzle would have to stay stationary for several minutes to cause damage. A tool with safety interlocks that would only be operational when attached to a girder would not be difficult to design. Finally, there is a high noise level associated with the process. However, the current method of removal also requires hearing protection.

CONCLUSIONS

Rivets from the Grand Narrows bridge were used for experimentation. Comparison of results from Rockwell Hardness tests and Spectrochemical Analyses of rivets from the Grand Narrows bridge to results for rivets from the Queen Victoria and Beverly Viaduct bridges have proven that the Grand Narrows' rivets are representative of the rivets that the Canadian National Railway is replacing.

Information from Trexler Industries, a local laser cutting company, has revealed that a laser beam can only cut most effectively up to 1/8-inch thick material. The beam loses its intensity beyond 1/4-inch cutting thickness. Therefore, a tool utilizing lasers to remove a rivet shaft from its hole would have to move into the hole to keep a constant cutting depth at all times. These opinions were reiterated by the president of Laser Applications, Inc.

Laser cutting causes heat buildup which develops substantial dross around the hole and requires a secondary finishing operation. For these reasons, as well as those of limited research time and money, the researchers decided to discontinue studies on laser cutting and to focus their efforts on more feasible developments.

A static load test, conducted on a section of a Grand Narrows' bridge girder, verified that hydraulics are powerful enough to remove most structural rivets. However, backing out a rivet from plates with severe misalignment could require a large enough force to actually damage the girder. A hydraulic tool that could perform a rivet removal task quickly and with little effort would have to be large in order to provide the reaction force. Due to the existence of small clearances in most cases, the tool would not be feasible. However, as stated earlier, a smaller hydraulic tool could be designed, but only for the purpose of removing the rivet head. Further tests would be required to verify that the tool would not slip from the rivets. A hydraulic tool designed to push the rivet shafts out of the holes would have to clamp onto the girder itself, using the girder to resist the application forces. The geometry of the girder is such that the hydraulic tool would have to be large enough to properly attach itself onto the girder. But small clearances, often only a few inches, would not permit this size tool.

The Canadian National Railway's consistent use of pneumatic tools has demonstrated that pneumatics are quick and effective when they work, but require strenuous physical exertion. The weight of the tool results in substantial loss in actual removal time since an ironworker has to rest at frequent intervals. However, the weight is needed since it provides the mass to form a reaction force for the tool to work against.

As far as adapting a better chisel to the pneumatic tool, the researchers concluded that the power of a pneumatic hammer plays a more crucial role than the condition of a chisel in simplifying the rivet removal process. The pneumatic hammer borrowed from Bethlehem Steel was notably smaller than that used by the Canadian National Railway and not powerful enough to remove a rivet in a desirable amount of time. A larger hammer, called a rivet buster was used for the geometry and chisel sharpness test. One promising method to speed up the process is to use the back out punch as a chisel, thus eliminating the time to change tools.

Perhaps the removal procedure could be changed so that a lighter pneumatic tool would prove sufficient. An example would be to use liquid nitrogen to make the rivets brittle, increasing the ease of their removal, and permitting a smaller impact force provided by a smaller pneumatic tool.

Experiments using liquid nitrogen have proven that rivets can be cooled to their ductile-brittle transition temperature inexpensively with little effort. The experiment demonstrated that an effective liquid nitrogen delivery system is essential. The system could be made portable since two pounds or less of liquid nitrogen are needed to make a rivet brittle. The amount of local damage to the base material due to the use of liquid nitrogen followed by impact forces; however, remains uncertain.

A powder actuated tool, on the other hand, behaves just like a pneumatic hammer in that it delivers an impact force through a piston. The advantages over a pneumatic tool are that a powder actuation tool is self contained, lightweight, and relatively small. The disadvantage is that powder actuated tools would not have as high of a blows per minute rating as that of pneumatic tools. This results in slower removal rates. Since the researchers did not have the resources to construct a powder actuated prototype, the difference in speed could not be determined. The power of a powder actuated tool could be easily controlled through the use of various quantities of explosive powder. The design of the tool, therefore, should be simple and its construction relatively inexpensive. However, if many blows are required to remove a rivet, the cost of the power charges and the collection of used cartridges could be expensive.

Waterjet cutting experiments indicated that an abrasive waterjet tool would be feasible to remove rivets in plates less than 1-1/2 inches thick. Beyond this distance the feed rate is significantly reduced and the distortion increased. Although the procedure is effortless, it takes about 5 minutes to remove a rivet. Yet a standard rivet diameter makes an automated system utilizing waterjets very feasible. An automated system could operate more than one waterjet to increase the production rate. In situations over 1-1/2 inches thick, it might be feasible to design a tool to travel into the rivet hole as it cuts to prevent jagged edges. It is probable that this method would remove rivets faster because the nozzle would always be close to the base material, a condition which significantly increases cutting effectiveness.

The waterjet cutting experiment also indicated that the danger of the powerful waterjet stream could be more easily contained than anticipated. It could cut through human flesh over 15 feet away from the nozzle; however, the cutting effectiveness of the stream dissipates considerably as the distance from the nozzle increases. The stream flowing out of the cut, as observed in the experiment, would not damage adjacent girders.

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