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INDIANA DEPARTMENT OF TRANSPORTATION
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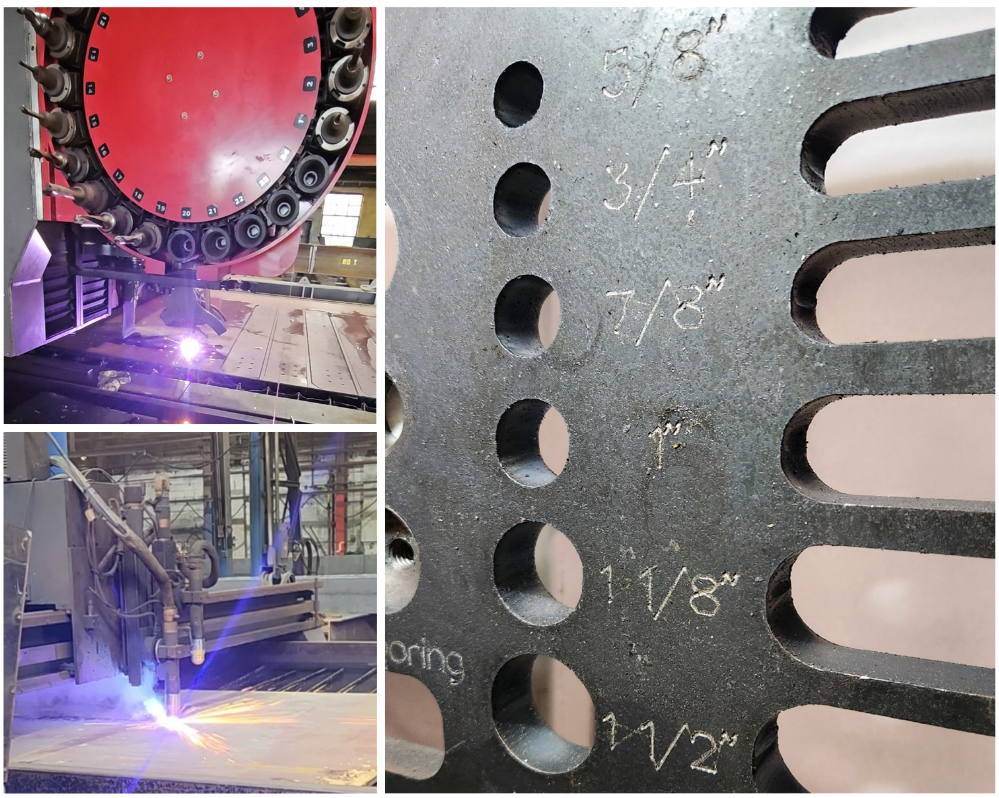
Fatigue Strength and Ductility of Steel Plates with Holes Made from Plasma Cutting Methods



Aurora Ebert, Robert J. Connor, Charles Kieffer III

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AUTHORS

Aurora Ebert, PE
Graduate Researcher
Lyles School of Civil and Construction Engineering
Purdue University

Robert J. Connor
Jack and Kay Hockema Professor of Civil Engineering
Director of the Center for Aging Infrastructure (CAI) and Steel Bridge Research, Inspection, Training and Engineering (S-BRITE) Center
Lyles School of Civil and Construction Engineering
Purdue University
(765) 496-8272
rconnor@purdue.edu
Corresponding Author

Charles Kieffer III, PE
Graduate Researcher
Lyles School of Civil and Construction Engineering
Purdue University

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16. Abstract

A literature review was conducted to evaluate current standards and existing research around the use of plasma arc cutting for holes (PACH) in the context of steel bridge applications. Additionally, an investigation into the state of the practice was conducted to determine if the latest technological advancements and equipment capabilities for plasma cutting could prove PACH to be an acceptable hole making process for bridge applications. Much of the existing research focuses on drilling and punching to make holes, but very limited experimental studies and data exists specifically evaluating plasma arc cutting. The most comprehensive study, including PACH, is discussed more thoroughly. Although limited, the findings from the existing research and the state of the practice are promising and suggest that plasma arc cutting may be acceptable as a hole making technique. To conclusively determine if such is the case, the research team recommends further experimental large-scale studies testing fatigue and strength at low temperatures.

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EXECUTIVE SUMMARY

Introduction

In the design and operation of steel bridges, load-induced fatigue is an important consideration. Due to the cyclic loading experienced by bridges, there is a need to focus on redundancy (load path, internal, and/or system redundancy). Because built-up members have been proven to provide great internal redundancy and welded connections are especially susceptible to fatigue cracking at the weld toe, bolted connections and bolted built-up members are advantageous in steel bridge construction. However, these methods require numerous bolt holes in the fabrication of bridge components.

Several hole-making processes exist in fabrication and their production speed and costs, hole quality, and fatigue, strength, and ductility performance vary. Only a few of the methods are considered acceptable in primary load-carrying members that are subject to cyclic loading in the structural steel codes and standards. Specifically, in the United States, the *AASHTO LRFD Bridge Construction Specification* (BCS) and the *RCSC Specification for Structural Joints Using High-Strength Bolts* (RCSC) are the specifications primarily used in bridge construction (AASHTO, 2017; Maljaars & Euler, 2021; RCSC, 2020). The BCS dictates that plasma cut holes can be used where full-size punching is allowed, generally in secondary members. The BCS allows for full size punched holes, "in fillers, cross frames, lateral bracing components, and the corresponding holes in connection plates between girders and cross frames or lateral components" (AASHTO, 2017). The RCSC specifies that for cyclic loading, thermally cut holes are permitted in slip-critical joints and were approved by the Engineer of Record (EOR) for other cyclically loaded joints. However, due to limited data on thermally cut holes in cyclic applications, it is not common for the EOR to approve the process. Although drilled and subpunched holes are acceptable in codes and standards, other techniques, such as plasma hole cutting, could provide improvements in production speed and a more efficient hole-making process.

Findings

A literature review was conducted to evaluate the current standards and existing research around the use of plasma arc cutting for holes (PACH) in the context of steel bridge applications. Additionally, the practice was investigated to determine if the latest technological advancements and equipment capabilities of plasma cutting make PACH an acceptable hole-making process for bridge applications. Much of the existing research focused on drilling and punching hole-making methods, and very few experimental studies specifically evaluated plasma arc cutting. Although limited, the findings from the existing research on the practice are promising and suggest that plasma arc cutting may be acceptable as a hole-making technique. To conclusively determine if such is the case, the research team (RT) recommends further experimental studies.

Implementation

Since there is little to no data available, large-scale testing of pretensioned bolted connections for both fatigue and strength should be conducted to determine if PACH is acceptable for bridge applications. Large-scale testing is critical to ensure that all "scale" effects (residual stresses, defect distribution, distortion effects, etc.) are integrated. Fatigue testing is expected to confirm previous experimental studies demonstrating PACH with pretensioned bolts to be a fatigue detail. Category B. Strength (tension) testing should be conducted under low temperature conditions to determine the ductility behavior of PACH at temperatures below 0°F. If the results of the large-scale testing determine PACH to be acceptable, the Indiana and AASHTO codes should be updated to include plasma arc cutting as an acceptable hole-making process for primary members subject to cyclic loading.

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1. INTRODUCTION

In the past decade, there have been numerous advancements in technology to produce thermally cut holes in steel plates and shapes, particularly in relation to plasma arc cutting of holes. Plasma cutting works through the simultaneous use of an inert gas and an electrical arc formed through that gas to create plasma, which is hot enough to melt the metal that is being cut (Garcia et al., 2015). The process can be used by hand for less critical cuts where geometry control is less important, like oxy-acetylene torches. For more critical geometry control, such as for making bolt holes, cutting heads are mounted to computer numerical control (CNC) machines for greater automation and efficiency.

During fabrication, PACH methods have proven to be more economical when compared to traditional hole drilling methods, and in some cases, demonstrate improved production speeds. Potential cost savings could also exist in the form of a reduced number of fabricator RFIs seeking approval for PACH processes if EOR approval requirements were removed from the standards and codes. Previous and ongoing research to evaluate these methods in terms of fatigue, ductility, geometry control, etc., exist and have been reviewed by the RT. Despite potential benefits, concerns remain in the industry around a negative impact on fatigue, strength, and ductility, particularly at low temperatures. The largest study to date on PACH was performed by FHWA to investigate these concerns. While the FHWA study, along with other previous and ongoing work, identified these concerns, it is evident that gaps still exist in the literature regarding these effects. While research findings do exist, it appears that the data has not been examined in its entirety to evaluate trends. Furthermore, as the technologies to use these methods are proprietary in nature, companies continue to improve their equipment to produce better quality holes. Thus, what may have been a concern or problem in the past, may no longer be a concern due to improvements in equipment and/or software. Despite improvements, concerns remain in industry. Finally, the current AASHTO Specifications limit the use of PACH to only secondary members due to these concerns even though it is unclear if these limitations are fully justified in all applications.

Based on the above, there was a need to examine and synthesize all of the existing data to (1) find the gaps in the literature; (2) determine the validity of the commonly raised concerns in terms of supporting data; (3) evaluate if the current concerns are justified in the context of actual in-service applications in highway bridges; and (4) identify the applications in highway bridges as to when such hole-making techniques are and are not appropriate and how to incorporate such recommendations into the Indiana and AASHTO bridge design specifications. Updates to current INDOT (and AASHTO) bridge design specifications will result in improved and updated design methods should the project find that PACH is viable and reliable.

2. LITERATURE REVIEW

A literature review was conducted to evaluate past experimental and analytical studies to determine the depth and findings around fatigue, strength, and ductility in bridge applications. The goal of the literature review was to focus on plasma arc cutting of holes. The review included research for open holes and bolted hole connections for thermally cut, drilled, and punched holes, as well as the behavior of plasma cut edges. This literature review describes the codes and specifications, previous research findings, ongoing research, and the state of the practice as it relates to the above-mentioned topics.

2.1 Codes and Specifications

Current codes and standards focus primarily on drilled and subpunched methods for hole cutting. Guidance for thermal cutting technologies in fatigue applications is limited. In the United States, the primary specifications addressing structural design and construction for bolts are the *AASHTO LRFD Bridge Construction Specification* (BCS), the *RCSC Specification for Structural Joints Using High-Strength Bolts* (RCSC), and the AISC 360-22 *Specification for Structural Steel Buildings* (AISC) (AASHTO, 2017; Maljaars & Euler, 2021; RCSC, 2020). The BCS dictates that plasma cut holes can be used where full-size punching is allowed, generally in secondary members. The BCS allows for holes to be punched full size "in fillers, cross frames, lateral bracing components, and the corresponding holes in connection plates between girders and cross frames or lateral components" (AASHTO, 2017). The RCSC specifies that for cyclic loading applications, thermally cut holes are permitted in slip-critical joints, or were approved by the Engineer of Record (EOR) for other cyclically loaded joints. Due to limited data on thermally cut holes in cyclic applications though, it is not common for the EOR to approve the process. Finally, the AISC does allow plasma arc cutting for cutting material up to 1.5 inches but recommends consulting equipment manufacturers before cutting plate thicknesses greater than 1.5 inches. However, the AISC outlines specifications for structural steel buildings, which are typically statically loaded and not fully aligned with our focus for fatigue applications (AISC, 2023).

Globally, some of the steel construction codes include European code BS EN 1090-2:2018 (BSI, 2018), Canadian code CSA S16:19 (CSA Group, 2019), and Australian/New Zealand AS/NZS 5131:2016 (Joint Technical Committee BD-001, 2016). The British Standard dictates that any method of hole making can be used provided that certain hardness, surface quality, and assembly requirements are met. Determining whether plasma arc cut holes meet these requirements would need to be confirmed by the engineer, fabricator, and inspector. For cyclic loading, punching without reaming or subsequent drilling is not permitted.

The Australia/New Zealand Standard (AS/NZS) is similar in that it generally permits all hole-making processes provided certain geometric and quality requirements are met, and no burrs or rough edges are present. The AS/NZS makes no specific mention of cyclic loading. The Canadian Standard allows thermally cut holes in statically loaded structures but makes no mention of whether plasma cutting can be used for holes in cyclically loaded applications.

2.2 Previous Research

Due to how recent technological advances are in plasma arc cutting, much of the existing research has been focused on the performance of drilled and punched holes. Limited experimental studies exist around hole making using plasma arc cutting, but the available publications have been included in the literature review. Appendix A includes the detailed report for the literature portion of this project.

Over the last 50 years, experimental studies have investigated specimens using drilled and punched holes with a specific focus on the influence of pretension, joint geometry, cyclic type loads, materials, surface treatment, and the hole cutting technology used. Experimental tests have specifically evaluated the effects of holes on strength, ductility, and fatigue performance of steel plates. One significant finding is the improvement in fatigue and tensile strength performance when using pretensioned bolts as compared to snug tightened bolts. Even though this study was focused on drilled and punched holes, the improvement observed in strength, ductility, and fatigue can also be expected for connections with plasma arc cut holes (Brown et al., 2007; Lubitz, 2005; Zampieri, 2019). Research around plasma cutting for edges was conducted as early as 1997 by the Transportation Research Board, but that specific research and experimental study was limited to plasma cut edges and did not investigate hole cutting (Harris, 1997).

The most comprehensive experimental study conducted for plasma arc cutting for holes in strength, ductility and fatigue is that of Beckett and Ocel (2020). The experimental study evaluated different methods of plasma arc cutting, each method varying by the level of operator intervention required. The nomenclature used by researchers in this specific study are not used commonly in industry but were categorized for the study as *conventional plasma arc cutting* and *enhanced hd plasma arc cutting* methods. Systems categorized as conventional methods included those that are highly mechanized gantry-type setups and place a high level of responsibility on the operator to set and maintain all cutting parameters throughout the cutting process, such as cutting speed, arc voltage, and gas flow, etc. Enhanced HD systems differ from conventional in that they are fully automated with CNC technology, such that the cutting parameters are adjusted by the computer in real-time to ensure hole quality. Fatigue tests were conducted on specimens with single open holes and specimens with a two-by-two connection configuration. The connection assembly for the two-by-two connection configuration used for fatigue testing is shown in Figure 2.1.

Snug tightened connections demonstrated a fatigue resistance Category E and the limited testing (four total specimens) on pretensioned tightened connections demonstrated a fatigue resistance Category B. For this reason, pretensioned connections should be a focus of future experimental studies. Another significant finding was that of the arc termination notch location and its effect on crack initiation. Figure 2.2 shows the arc termination notch positioning in relation to the direction of primary stress. The arc termination notch proved optimal when parallel to the stress flow because no specimens experienced the crack initiation at the notch when the notch was at this location (low stress concentration area shown as 90° in Figure 2.2). Because CNC on plasma arc cutting machinery allows the notch location to be easily programmed, a requirement for the location of the arc termination notch should be easy to implement in updated codes and standards and verify during fabrication inspection.

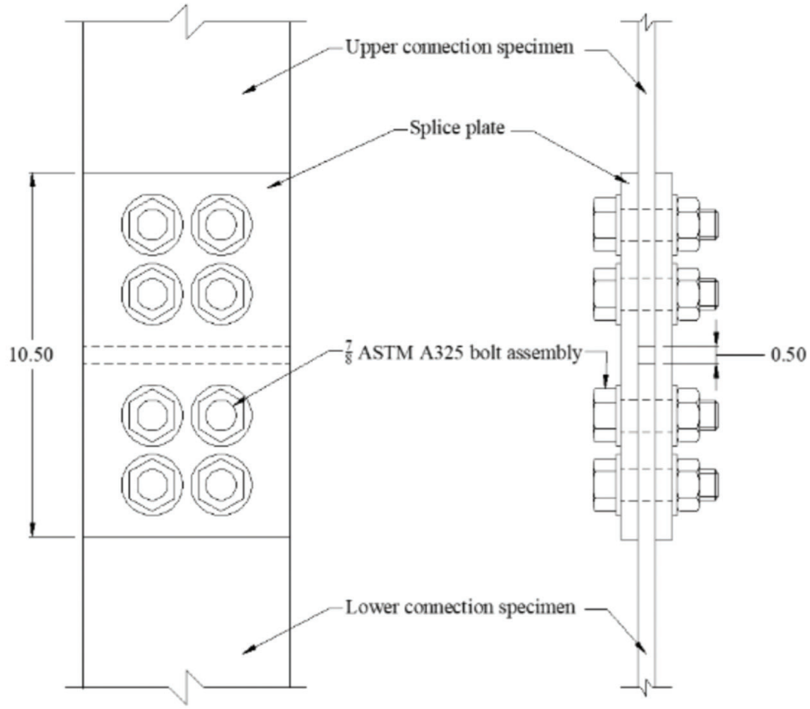
Ocel also conducted strength testing with plate specimens with a single open hole in the middle of the plate. Tests were conducted at both room temperature and low temperatures (below 0°F). Room temperature tests resulted in ductile failures, while the low temperature tests were a blend of brittle and ductile fractures. Further investigation around the influence of low temperature on ductility was recommended by the authors.

A similar experimental study conducted by Garcia and Cicero (2016) evaluated plasma arc cutting as well as flame and laser cutting on the fatigue behavior of thermally cut edges and holes. Their objective was to determine an AASHTO fatigue detail category for plasma and laser cut edges and flame, plasma, and laser cut holes. Garcia and Cicero confirmed the findings of Beckett and Ocel in that plasma cut open holes fell into the fatigue resistance Category E. For context, drilled and subpunched holes are fatigue resistance Category D.

Overall, results are somewhat limited due to the small number of existing studies and the fact that existing studies have been small-scale experiments. Experimental data looks promising for fatigue in pretensioned and slip-critical connections, but questions regarding the influence of temperature on ductility and the impact of fatigue remain. Specific recommendations for future testing based on current experimental data available are detailed in the Recommendations section of this report.

2.3 Ongoing Research

The benefits of a more efficient hole-making process for plasma arc cutting are alluring to many in industry and academia. In discussions with fellow academic colleagues, the RT learned that current research around plasma arc cutting is taking place at the University of Cincinnati (UC). The work at UC is very similar to the work done by Beckett and Ocel (2020). The team at UC



Source: FHWA.
Note: Units are in inches.

Figure 2.1 Fatigue specimen connection assembly (Beckett & Ocel, 2020).

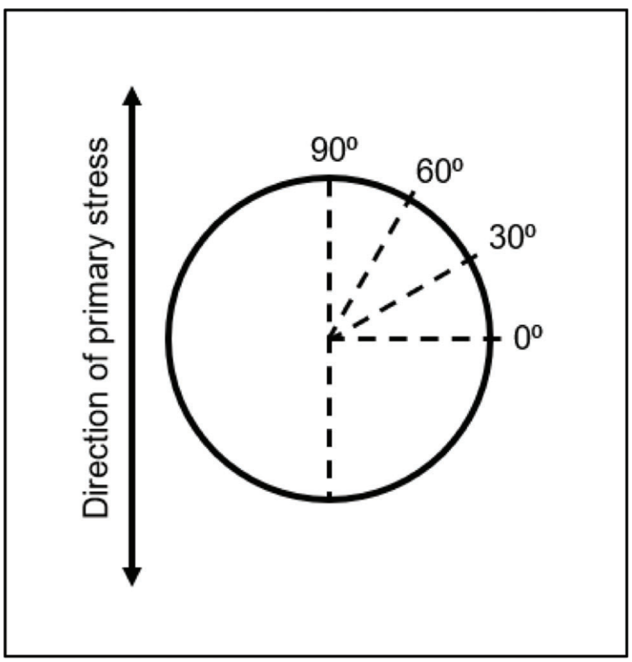


Figure 2.2 Arc termination notch positioning.

is investigating the performance of samples with holes using waterjet cutting, laser cutting, and plasma cutting under monotonic, seismic, and fatigue loading, and comparing that to the performance of drilled hole specimens. Specimens include three-by-one coupons, two-by-one bolted, and two-by-two bolted specimens. As the research is still ongoing, the findings are not published and cannot be discussed, specifically in this report. Although there is optimism for this current research, limitations exist as it is again a small-scale experimental study. The Purdue research team believes greater insight could be achieved with a large-scale experimental study and the parameters as defined in the recommendations section of this report.

2.4 State of the Practice

In addition to published research, the RT had opportunities to meet with industry professionals to understand the current technology used in practice. At the 2024 North American Steel Construction Conference (NASCC), the RT spoke with fabricators, manufacturers, and OEMs (original equipment manufacturers) to understand the process from varying perspectives. Multiple fabricators shared that their process for quality control focused mostly on geometry and ensuring that a bolt would fit properly. Equipment manufacturers confirmed the reliability of the CNC programming of the machines and the quality capability with technological advancements (for example, Hypertherm sells the True Hole technology with their XPR equipment, while Kjellberg sells ProPierce and Q-Hole to improve their equipment's performance). Kjellberg and Hypertherm are the leading OEMs in plasma arc cutting technologies. A representative from Kjellberg shared information about the plasma arc cutting process as well as documentation addressing the quality assessment of plasma cuts required for their equipment. Evaluation criteria include the presence of dross, surface roughness, hole geometry, perpendicularity, and bevel tolerances, etc. Formulas are also provided for the operator to input certain variables and output the proper speeds and feeds of the equipment and consumables for desired project results. Kinetic, a manufacturer of plasma arc cutting equipment, also shared information about technological advancements and the high level of automation that plasma arc cutting machines can achieve. The RT learned of the accuracy of CNC programming, including the ease of programming the location of the arc termination notch, and the improvements that ongoing technological advancements are making for hole quality using plasma arc cutting. The information gathered gives the RT confidence in dictating the arc termination notch location and hole quality that can be achieved for steel bridge applications, which would then be inspected for quality control in fabrication using the same procedures and sampling methods as is done for drilling.

The RT also had the opportunity to participate in a facility tour at Wabash Steel in Vincennes, Indiana. Demonstrations were provided for both plasma cutting tables on site, including the Kinetic table that has both plasma arc cutting and drilling capabilities (both tables are shown in Figure 2.3).

Wabash Steel operators not only demonstrated the equipment, but also answered questions about consumables, the performance life of consumables, quality control, automation capabilities, and much more. One concern was regarding the reduction in hole quality as the consumables wear, but it was learned that the variance in hole quality between using a new consumable and a worn consumable is small. Furthermore, the plasma arc cutting tables keep track of the number of cycles consumed and how many remaining cycles are available. However, what constitutes a "cycle" in the context of hole as a function of hole quality will need to be further explored. The information available to the operator, along with their expertise of the equipment, allows for greater consistency in hole quality throughout the consumable life. The tour gave greater confidence to the team around the hole quality and automation capabilities that can be achieved in plasma arc cutting.

Although it is too soon to comment on fatigue results, it is important to note that plasma arc cutting for holes was recently used in a steel bridge project in the state of Indiana (HNTB, personal communication, October 4, 2022). Under the guidance of FHWA on redundancy, one of two steel press brake bolted tub girder bridges was constructed using plasma cut holes. The evaluation of the fatigue stresses for the single span tub girder demonstrated a stress range of 3.6 ksi, which is less than the constant amplitude fatigue threshold (CAFL) of 4.5 ksi for a fatigue detail Category E. The project used pretensioned bolts as well, which should provide a Category B detail based on the limited existing research (Beckett & Ocel, 2020). Given the small stress range, the fabricator on the tub girder project was permitted to use plasma cut holes for the single span tub girder bridge. It should be noted that a two span tub girder bridge was fabricated with drilled holes, so INDOT and HNTB will be able to directly compare the long-term performance of drilled and plasma cut holes.

2.5 Summary

Although most of the existing research available evaluated the hole-making processes of drilling and punching, experimental data and findings are still applicable in plasma cutting research. Findings from the literature and information from the current industry practices and technology advancements indicate that plasma arc cutting could prove adequate for cyclic loading applications. Future research should be focused on large-scale experiments using CNC fully automated plasma cutting methods and pretensioned bolted connections. Additionally, the arc termination notch should be specified to be located at a low stress concentration area and low temperature testing should be conducted for strength and ductility evaluation.

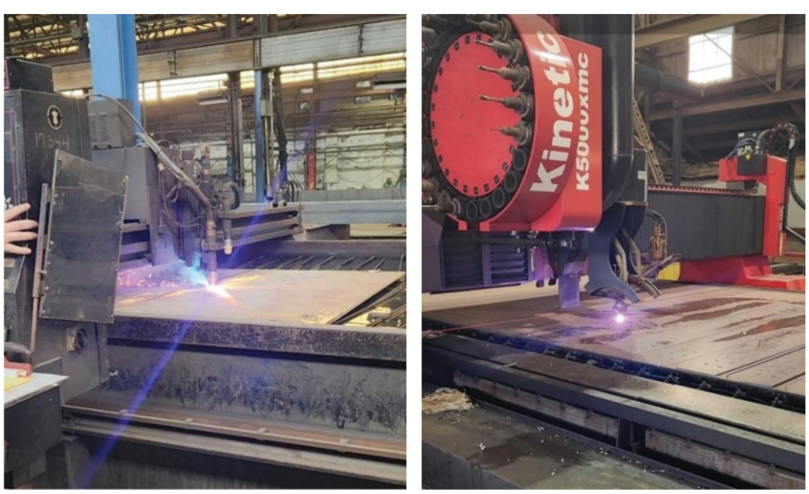


Figure 2.3 Wabash steel plasma arc cutting equipment.

3. RECOMMENDATIONS

Based on the review of existing research and state of the practice investigation, the RT has determined that a large-scale experimental study is critical in determining the specific circumstances where plasma cut holes are acceptable for bridges. The existing data, though limited, does suggest that plasma cutting of holes will be acceptable where both fatigue and strength limit states are of concern. However, the limitations (if any) need to be further vetted. Large-scale testing is critical in ensuring that all "scale" effects (residual stresses, defect distribution, distortion effects, etc.) are integrated in the specimens. For example, in fatigue, a given specimen will likely contain a few hundred holes, whereas in a small-scale specimen, only 2 or 3 holes may exist. Since multiple large-scale fatigue specimens will be fabricated, a few thousand holes will be included in the testing program. The challenges of fabricating specimens with many holes will allow for tolerances to be evaluated along with defect distribution in the context of a more realistic specimen. This is why fatigue testing must be done at a realistic scale, as it is well known that small-scale fatigue tests are well known to overestimate the fatigue resistance of a given detail. (*The reasons, stated above, are analogous to a weak link theory. If 100 individual links of a chain are tested and there is only one "weak link" then one would conclude a 1% failure rate is reasonable. However, if two 50-link chains were tested from the same group of links, the failure rate is now 50%.*) Further, scale effects will also be present in the larger ductility tests that will are proposed. Finally, there is some truth in that the bridge industry takes the "show me" approach and hence, data obtained from larger-scale specimens will go a long way in the industry gaining confidence in the use of PACH for bridge applications. As such, the RT recommends the following proposal for future research to determine the validity of plasma arc cutting for holes when subject to cyclic loading.

3.1 Specimen Design and Fabrication

Strength and fatigue testing will vary across test setup and specimen geometry. The experimental study will focus on pretensioned bolted connections for both fatigue and strength testing. Open hole specimens are not required because they have already been tested with sufficient data and results can be found in the literature review in Appendix A. Further, when used in bolted joints, the fasteners are always fully pretensioned in bridge applications and hence, there is no need to investigate snug tight applications. Previous research findings did not show a significant change in behavior due to steel grade, so steel grade will not be a variable parameter that should be evaluated in the experimental study. A specific steel grade should be specified to each fabricator so that each specimen uses the same steel grade and the parameter remains controlled. The RT recommends standardizing the steel grade at A709 50 ksi.

The literature review suggests it is more important to account for the variability across fabricators and equipment. Therefore, it is proposed the experiment obtain specimens from at least three or more different fabricators. Doing so will account for the variability across fabricators and equipment to ensure that any research findings and conclusions are representative of the state of the practice. This will also facilitate adoption for updating codes and standards across all possible fabricators and minimize the need to specify a specific fabricator or specific equipment.

However, at a minimum, all specimens should be made using CNC programming (automated) plasma arc cutting equipment. The arc termination notch should be programmed parallel to the stress flow, or in other words, at the location of the lowest stress concentration for all holes (shown as 90° in Figure 2.2). All specimens shall be visually inspected for hole quality prior to testing with regards to hole geometry (roundness, diameter, conical taper angle, start/stop detail, etc.) and surface imperfections. Measuring the extent of the heat affected zone (HAZ) should be also done for ductility analysis in correlation with the strength testing.

At present, it is proposed the experimental program be comprised of thirty-nine total specimens, eighteen specimens for fatigue and twenty-one for strength testing. Three fabricators will provide three specimens of a lower bound thickness of ½″ and three specimens of an upper bound thickness of 1-¼″ (six specimens for fatigue and six for strength testing). Each fabricator will provide an additional specimen using drilled holes for a baseline comparison for strength testing. Table 3.1 shows the specimen detail and nomenclature.

3.2 Strength Test

The purpose of conducting the strength test is to determine if there is an influence on ductility associated with PACH. During all thermal cutting processes, an HAZ develops. The HAZ is the area of metal that has not been fully melted but has been exposed to high temperatures and has thus undergone property changes. This process typically increases the hardness of the material in the HAZ relative to the base metal, which can increase the risk of brittle behavior. Previous experimental studies evaluated the ductility of specimens with holes made using PACH with single open holes at both room temperature and low temperatures. All room temperature specimens exhibited acceptable ductile behavior. However, the low temperature specimens were a blend of ductile and brittle failures (Beckett & Ocel, 2020). The low temperature test results recorded actual temperature ranges between -17°F to 4°F. In addition to testing specimens with PACH, three specimens of the same plate material with drilled holes (one specimen from each fabricator) should also be tested to set a baseline for performance.

While these data are very useful, the use of plates with open holes is quite limited. Therefore, the RT recommends conducting all strength tests at tempera-

TABLE 3.1
Specimen nomenclature

Fabricator	Plate Thickness (in)	Cutting Process	Fatigue Specimen Nomenclature	Strength Specimen Nomenclature
A	½	Plasma	FA-0.5-1	SA-0.5-1
		Plasma	FA-0.5-2	SA-0.5-2
		Plasma	FA-0.5-3	SA-0.5-3
	1-¼	Plasma	FA-1.25-1	SA-1.25-1
		Plasma	FA-1.25-2	SA-1.25-2
		Plasma	FA-1.25-3	SA-1.25-3
		Drilled	N/A	SA-1.25-D
B	½	Plasma	FB-0.5-1	SB-0.5-1
		Plasma	FB-0.5-2	SB-0.5-2
		Plasma	FB-0.5-3	SB-0.5-3
	1-¼	Plasma	FB-1.25-1	SB-1.25-1
		Plasma	FB-1.25-2	SB-1.25-2
		Plasma	FB-1.25-3	SB-1.25-3
		Drilled	N/A	SB-1.25-D
C	½	Plasma	FC-0.5-1	SC-0.5-1
		Plasma	FC-0.5-2	SC-0.5-2
		Plasma	FC-0.5-3	SC-0.5-3
	1-¼	Plasma	FC-1.25-1	SC-1.25-1
		Plasma	FC-1.25-2	SC-1.25-2
		Plasma	FC-1.25-3	SC-1.25-3
		Drilled	N/A	SC-1.25-D

Note: The letter indicates fatigue or strength (F or S), followed by fabricator ID (A, B, or C). The first number is the plate thickness (0.5 inch or 1.25 inch), and the final number is the specimen number for the given fabricator and thickness. For example, "SA-0.5-1" is specimen 1 from Fabricator A with a 0.5-inch thickness and "SA-0.5-2" is specimen 2 from fabricator A with 0.5-inch thickness.

tures below 0°F in specimens that utilize spliced pretensioned bolted specimens. Each individual specimen should be a single plate with PACH and pretensioned 7/8-inch diameter high strength bolts (four to eight) installed in the holes. While the bolts will be fully pretensioned, the fasteners will go into bearing upon slip. As a baseline for comparison, three baseline specimens will be fabricated using drilled holes.

3.2.1 Fatigue Test

Specimens for the fatigue test will be steel plates as described in Table 3.1 acting as either splice plates or cover plates, depending on the test setup option selected as described in the Test Setup Section below. The precise bolt pattern will depend on which setup option is selected, but pretensioned 7/8-inch diameter high strength bolts will be used for PACH evaluation.

3.3 Test Setup

Because the existing data is limited to four specimens for fatigue testing using pretensioned bolts and strength tests were completed using only open holes (Beckett & Ocel, 2020), as stated the RT recommends doing further fatigue testing as well as tension strength testing using pretensioned bolted connections. It is anticipated that fatigue testing will confirm a fatigue resistance Category B for pretensioned bolts in plasma cut holes. For context, Beckett and Ocel found snug-tightened bolted connections to be as low as Category E, but pretensioned bolts demonstrated a Category B. Beckett and Ocel did not conduct tension testing for pretensioned bolts using PACH. The goal for strength testing is to establish ductile behavior for PACH when subject to low temperatures.

3.3.1 Strength Test

For the strength testing, the RT recommends large-scale axial testing specimens with PACH. For illustrative purposes, a similar test set up from a previous experiment at Bowen Laboratory is shown in Figure 3.1. This test frame can apply up to 2.2 million pounds in tension. Further, a servo-controlled MTS universal testing machine capable of applying 700 kips is also available for testing. Holes used to connect the specimen to the fixture should be PACH, while any holes in fixture components should be drilled holes. The current proposed strength test specimen matrix is shown in Table 3.2.

3.3.2 Fatigue Test

For the fatigue testing portion, it is recommended to conduct a set of large-scale experiments with rolled I-section girders using bolted connections to attach the specimen plates. Any components that are considered part of the setup or fixture shall use drilled holes, while any components considered specimens for testing shall use plasma cut holes. Two testing variations are being explored for fatigue and depictions of the various options are shown in Figure 3.2 and Figure 3.3. Bowen Laboratory has two available test frames as shown in Figure 3.2, allowing two beams to be fatigue tested at the same time.

Figure 3.1 Illustrative example for axial test setup (Lloyd, 2018).

Option 1 will include a single span I-beam with the specimen plates attached as cover plates. The length of the plate should be sufficiently long such that the plate is fully developed for shear transfer. Option 2 will include two I-beams of the same size that are connected with splice plates to simulate a girder splice. This option ensures that the specimen plates will carry the full stress of the test based on the principles of load transfer. Figure 3.3 shows only the beam without the fixture for clarity. Fatigue testing for both Options 1 and 2 should be conducted to explore fatigue behavior of PACH in different types of member components. The test matrix will be updated when the final count of each specimen type is determined.

Per INDOT Chapter 407, web thickness shall be a minimum of 1/2 inch. Similarly, AASHTO dictates a minimum flange plate thickness of 3/4 inch. Bolts shall be 7/8-inch diameter ASTM A325 high strength bolts, as is typical in bridge design. The web and flange dimensions will be important in determining a W-shape for the fixture portion of the fatigue testing. The specimen plate thickness will utilize an upper bound and lower bound thickness as described previously. The fatigue test matrix is outlined in Table 3.3. A proposed starting stress range of 18 to 20 ksi is proposed as Category B CAFL is 16 ksi. If cracking below Category B is observed, then the stress range will be lowered to something in range of 12–14 ksi to evaluate the applications of Category C. All tests in the finite life region will be run to the upper-bound fatigue life

TABLE 3.2
Strength test matrix

Specimen ID	Nomenclature	Temperature	Pretensioning	Target Load
19	SA-0.5-1	Below 0°F (record exact during testing)	Yes	F_uA_{net}
20	SA-0.5-2		Yes	F_uA_{net}
21	SA-0.5-3		Yes	F_uA_{net}
22	SA-1.25-1		Yes	F_uA_{net}
23	SA-1.25-2		Yes	F_uA_{net}
24	SA-1.25-3		Yes	F_uA_{net}
25	SA-1.25-D		Yes	F_uA_{net}
26	SB-0.5-1		Yes	F_uA_{net}
27	SB-0.5-2		Yes	F_uA_{net}
28	SB-0.5-3		Yes	F_uA_{net}
29	SB-1.25-1		Yes	F_uA_{net}
30	SB-1.25-2		Yes	F_uA_{net}
31	SB-1.25-3		Yes	F_uA_{net}
32	SB-1.25-D		Yes	F_uA_{net}
33	SC-0.5-1		Yes	F_uA_{net}
34	SC-0.5-2		Yes	F_uA_{net}
35	SC-0.5-3		Yes	F_uA_{net}
36	SC-1.25-1		Yes	F_uA_{net}
37	SC-1.25-2		Yes	F_uA_{net}
38	SC-1.25-3		Yes	F_uA_{net}
39	SC-1.25-D		Yes	F_uA_{net}

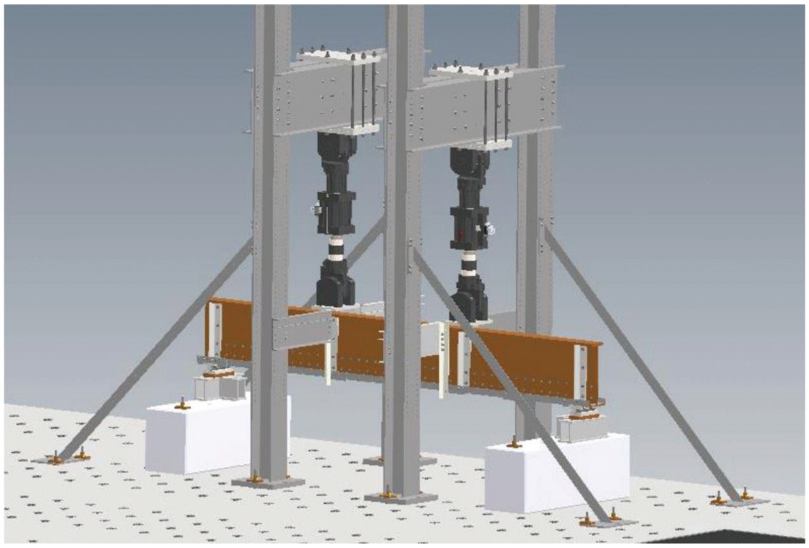


Figure 3.2 Fatigue Option 1 specimen as cover plate.

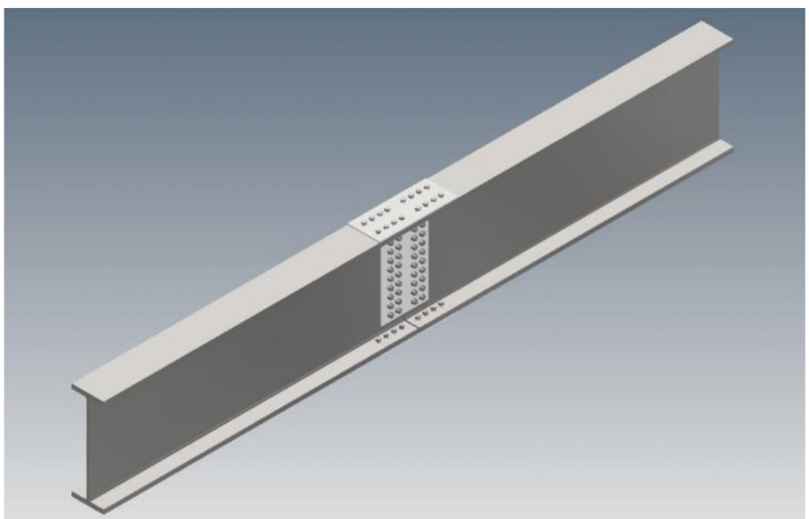


Figure 3.3 Fatigue Option 2 specimen as splice plates.

(i.e., the mean plus two standard deviations for the given category).

3.4 Failure Criterion

During fatigue and tension testing, visual inspection will be used to observe crack initiation and propagation. The failure criterion in fatigue testing will be measured as a 10% reduction in stiffness. The tension testing will be observed for brittle or ductile fracture of the plate specimens and results compared to the baseline specimen data. Tension testing will be conducted at cold temperatures less than 0°F to evaluate ductility.

TABLE 3.3
Fatigue test matrix

Specimen ID	Nomenclature	S_{max}	S_{min}	S_r
1	FA-0.5-1	20	2	18
2	FA-0.5-2	20	2	18
3	FA-0.5-3	20	2	18
4	FA-1.25-1	20	2	18
5	FA-1.25-2	20	2	18
6	FA-1.25-3	20	2	18
7	FB-0.5-1	20	2	18
8	FB-0.5-2	20	2	18
9	FB-0.5-3	20	2	18
10	FB-1.25-1	20	2	18
11	FB-1.25-2	20	2	18
12	FB-1.25-3	20	2	18
13	FC-0.5-1	20	2	18
14	FC-0.5-2	20	2	18
15	FC-0.5-3	20	2	18
16	FC-1.25-1	20	2	18
17	FC-1.25-2	20	2	18
18	FC-1.25-3	20	2	18

4. CONCLUSION

During fabrication, PACH methods have proven to be more economical when compared to traditional hole drilling methods, and in some cases, demonstrate improved production speeds. Due to the need to examine and synthesize existing data, the RT conducted a literature review around PACH. The literature review revealed the need for a large-scale study to determine whether PACH could be acceptable for cyclic loading applications. Existing research is limited to small scale testing and provides limited data to definitively allow PACH in bridge applications. Large-scale testing should provide more conclusive results to determine the validity of the commonly raised concerns in terms of supporting data, evaluate if the current concerns are justified in the context of actual in-service applications in highway bridges, and identify the applications in highway bridges as to when such hole-making techniques are and are not appropriate. Based on prior experimental studies, the RT anticipates PACH with pretensioned bolts to fall into fatigue detail Category B. Additionally, the ductility of PACH using pretensioned bolts should be evaluated through strength testing at low temperatures. Updates to current INDOT (and AASHTO) bridge design specifications will result in improved and updated design methods should the project find that PACH is viable and reliable.

Such large-scale testing will require a reasonable investment by INDOT. It may be possible to have steel donated as well as some fabrication donated. Further, it may be possible to obtain support from other states or agencies through the TPF process. However, identifying and securing external funding will of course take time. Therefore, the research team proposes that INDOT provide "kick-off" funding to initiate the strength testing portion of the work. If possible, it would also be prudent to conduct a few fatigue tests as sort of a pilot study to obtain data to further justify the benefits of further fatigue testing.

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Garcia, T., Cicero, S., Ibanez, F. T., Alvarez, J. A., Martín-Meizoso, A., Bannister, A., Klimpel, A., & Aldazabal, J. (2015). Fatigue performance of thermally cut bolt holes in structural steel S460M. *Procedia Engineering*, *133*, 590–602.

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Maljaars, J., & Euler, M. (2021). Fatigue S-N curves of bolts and bolted connections for application in civil engineering structures. *International Journal of Fatigue*, *151*, 106355.

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Zampieri, P., Curtarello, A., Maiorana, E., & Pellegrino, C. (2019). A review of the fatigue strength of shear bolted connections. *International Journal of Steel Structures*, *19*, 1084–1098. https://doi.org/10.1007/s13296-018-0189-5

APPENDICES

Appendix A. Literature Review

APPENDIX A. LITERATURE REVIEW

Beckett, C., & Ocel, J. (2020). *Evaluation of holes fabricated using plasma arc cutting* (Report No. FHWA-HRT-20-056). Professional Service Industries, Inc. https://highways.dot.gov/sites/fhwa.dot.gov/files/FHWA-HRT-20-056.pdf

The experimental study and subsequent report are the most comprehensive and relevant to our research goals in our collection of references. The experimental study evaluated plasma arc cut holes for fatigue, ductility, and strength with some comparison to drilled holes. The report outlines the different plasma arc cutting process types used on the specimens (the variation due to the level of operator intervention in each process), the evaluation of hole quality as defined by AASHTO specifications, and fatigue and strength performance. The authors provide some recommendations for potential future work in this area.

Three types of plasma arc cutting are introduced. The types are referred to as conventional, high-definition, and enhanced plasma arc cutting method, with the variation due to a decrease in operator intervention, in that order respectively. It should be noted that this terminology is not consistently used across fabricators, manufactures, etc., and cannot be reliably expected to be understood by everyone in research and industry. The study included plasma arc cut holes using the conventional and enhanced methods.

Hole quality was compared between plasma arc cut, punched, and drilled holes. Hole quality is defined by evaluating roundness, surface imperfections, and geometric features (diameter, eccentricity, circularity, conical taper angle, heat affected zone and hardness). The enhanced plasma arc cutting process produced higher quality holes than the conventional process. The hole quality using the conventional process would not be sufficient for bridge fabrication. The enhanced process would be acceptable if the bridge-construction industry would accept larger diameter tolerances (currently requires a 1/32-inch tolerance, but the enhanced process would require a 1/16-inch hole diameter tolerance).

Fatigue resistance was tested using two types of specimens: a single open-hole (referred to as the plate-fatigue specimen) and a two-by-two bolted pattern at one end tested in pairs as a bolted butt splice (referred to as the connection specimen). AASHTO currently classifies open holes as Category D; plasma-cut open holes demonstrated Category E fatigue performance. Plasma-cut snug-tightened bolts demonstrated Category E. Four connection specimens were tested with pretensioned bolts in the connection-type specimen using holes cut via the conventional process, as compared to the hundreds of specimens tested as snug-tightened. The very limited study showed an improvement to Category B. The authors recommended that future work should focus on pretensioned bolted connections from holes cut with the enhanced process. Additionally, the arc-termination notch orientation was evaluated, and it was concluded that the notch should be programmed using CNC technology to require the notch be parallel with the stress flow.

Strength testing (referred to in the report as tensile resistance) was completed on specimens of a single plasma-cut hole in the middle of the plate. Because the heat affected zone was a concern for ductility and strength, tests were done at both room temperature and low temperatures (below zero degrees Fahrenheit). Unfortunately, it was inconclusive whether the brittle behavior was caused by the steel itself or by the plasma-cutting process because there was no excess steel at the end of the study to decouple the two variables. All room temperatures tests resulted in ductile failures, whereas the low temperatures resulted in a mix of both brittle and ductile fractures depending on the loading rate and whether the specimen was cut by the conventional or enhanced method. Testing variables were focused on test temperature and loading rate because they have the greatest effect on fracture performance. It was noted in the report that all specimens demonstrated yield ratios greater than 1.0, indicating that every specimen could develop the theoretical yield strength across the gross section, but not all could attain the theoretical fracture strength on the net section. To evaluate the influence of the hole cutting process, a limited size of specimens with drilled holes were compared to the plasma-cut specimens. Results for the specimens with drilled holes aligned most closely with the cluster of data for enhanced plasma-cut holes, thus indicating that the enhanced plasma arc cutting process did not influence the static performance of net sections, though the drilled holes did show a slightly better elongation. The conventional plasma cutting process proved unacceptable for strength and ductility performance. In general, it was concluded that the tension data indicated that the enhanced plasma cutting method is acceptable for use in cutting holes for grade 50W steel.

Moving forward with research around plasma arc cutting holes, the authors recommend that only grade 50W steel using the enhanced plasma arc cutting process should be used in future testing for strength and ductility research. Similarly, research for fatigue, strength, and ductility should focus on pretensioned bolt connections only.

Brown, J. D., Lubitz, D. J., Cekov, Y. C., Frank, K. H., & Keating, P. B. (2007). *Evaluation of influence of hole making upon the performance of structural steel plates and connections* (Report No. FHWA/TX-07/0-4624-1). The University of Texas at Austin Center for Transportation Research. https://ctr.utexas.edu/wp-content/uploads/pubs/0_4624_1.pdf

The technical report is based on a large experimental study of the effects of holes on strength, ductility, and fatigue performance of structural steel plates. Parameters included steel strength, plate thickness, hole size, punch to die clearance, galvanizing, temperature, and edge distance. Overall, results agreed with previous research that plates with punched holes have lower strength, ductility, and fatigue performance than plates with drilled holes.

The research focused on the hole cutting technologies of punched and drilled holes. Unfortunately, this experimental study did not include plasma arc cutting nor similar thermal cutting technologies in the research. One interesting finding was discovered unintentionally, and although it is not the focus of the results, it is thought-provoking regardless. Initially, the drilled holes were drilled using a worn drill bit. The RT noticed that these holes were demonstrating a fatigue life lower than expected, and once changed to a new drill bit, the fatigue performance was as expected for drilled holes. The specimens drilled with a worn drill bit had fatigue lives approximately equal to many of the punched hole specimens, despite being drilled. The subpunched and reamed specimens had the highest fatigue life, comparable to drilled holes (with a new drill bit).

Even though the study did not evaluate plasma arc cut holes, the findings of this experiment are pertinent to our goals in researching plasma arc cutting. The experimental study compared results from snug tightened bolts to pretensioned bolts and found that “the use of pretensioned bolts was shown to remarkably increase the experimental strength of both the punched and drilled specimens due to the extra capacity from friction.” If pre-tensioning bolted connections improved both fatigue and tensile strength performance for drilled and punched holes, we should expect that pre-tensioning bolted connections should also increase fatigue and tensile strength for plasma arc cut holes. Given that current AASHTO standards require joints to be designed as slip-critical type connections when subject to fatigue loadings, we should be able to consider the benefit of pre-tensioning the bolted connection as typical for bridge applications.

Garcia, T., Cicero, S., Ibanez, F. T., Alvarez, J. A., Martín-Meizoso, A., Bannister, A., Klimpel, A., & Aldazabal, J. (2015). Fatigue performance of thermally cut bolt holes in structural steel S460M. *Procedia Engineering*, *133*, 590–602.

Because current fatigue codes limit the use of thermal cutting processes and focus primarily on drilled and punched holes, this experimental study evaluated the fatigue performance of thermally cut bolt holes, specifically on structural steel S460M plates. The specific thermal cutting processes studied were oxy-fuel, plasma, and laser cutting. Thermal cutting processes are based on melting the metal to cut the steel, with the difference between the three being the methodology by which the metal is melted. Further details of these differences are outlined in the report. The benefits of thermal cutting processes are increased productivity and the ability to complete precise intricate geometries. Despite these benefits, current codes permit thermally cut holes for cyclically loaded joints “if approved by the Engineer of Record”, but with no data to show how these holes perform under fatigue loading, it is not typical for the EOR to approve thermal cutting processes for fatigue applications. Thus, the goals of this report are to not only evaluate the three processes of thermally cut holes, but also to extrapolate the standard S-N curves to thermally cut holes.

In total, 30 fatigue tests were completed, including 10 specimens of each type of thermal cutting process. Specimens were made up of a straight steel plate with a single open hole centered in the plate. Of the three thermal cutting processes, the surface quality was best with the plasma-cut surface. Fatigue behavior was evaluated based on the S-N curves and the fatigue limit, where infinite fatigue was defined as 10^7 cycles. For each cutting method, a corresponding S-N curve was constructed, and the mean curve plotted on the same graph for all three methods and later compared to the fatigue behavior of drilled and punched holes. The oxy-fuel cutting method resulted in the highest fatigue performance of the thermal cut processes, but just slightly higher than the laser and plasma cutting. Nonetheless, the laser and plasma cut holes demonstrated similar fatigue resistance to that of the drilled holes. The fatigue resistance for punched holes was lower than all thermally cut processes. Current codes deem an open hole (drilled or reamed) to be a fatigue detail Category D. The experimental results of this study determine the plasma cut holes to be a Category F, according to the European code BS7608. Unfortunately, this study did not report fatigue detail categories according to the AASHTO categorizations.

The project was thorough in including multiple processes for thermally cut holes, but testing only thirty total specimens could be considered a limited study. Additionally, while the results were compared to the European/British standards for fatigue categories, it would have been beneficial to also compare the S-N curves to the AASHTO fatigue categories. Given that the results indicate thermally cut holes have fatigue resistance between drilled and punched holes, there is reasonable belief that plasma cut holes could be acceptable for fatigue applications when designed according to the stress limits of the specific detail category.

Garcia, T., & Cicero, S. (2016). Proposal of AASHTO fatigue detail categories for structural steels containing thermally cut edges and cut holes. *Journal of Materials in Civil Engineering*, *28*(12). https://ascelibrary.org/doi/10.1061/%28ASCE%29MT.1943-5533.0001643

Similar to the paper "Fatigue Performance of Thermally Cut Bolt Holes in Structural Steel S460M" by the same author, this publication evaluates the fatigue behavior for the thermal cutting processes of flame, plasma, and laser cutting for thermally cut holes and edges. The experimental study in this paper evaluates 300 fatigue specimens using different steels (S355M, S460M, 690Q, and S890Q). The study constructs the S-N curves with the goal to estimate the AASHTO detail categories for each thermal cutting process.

Fabrication technologies allow plasma cutting and laser cutting processes to provide quality cuts at faster production speeds than drilling and punching. Surface quality is particularly important in fatigue applications because surface quality has a significant influence on the material fatigue strength. Of the three thermal cutting processes studied, the plasma cut holes resulted in the lowest roughness. Current codes and standards do not reflect the improved performance of thermal cutting technologies and detail categories are limited to flame cut edges or require extremely conservative parameters which cannot be met by plasma and laser cutting processes. The *Specification for Structural Joints Using High-Strength Bolts* (RCSC, 2009) does permit thermally cut holes for cyclically loaded applications when approved by the Engineer of Record. Approval from the EOR is not typically given due to the lack of data to show how thermally cut holes perform in fatigue applications. If the behavior of thermally cut holes in fatigue loading could be determined, fabrication costs and produce speeds could be significantly improved.

The results of a qualitative evaluation indicate that the surface quality is best for plasma cut holes due to the absence of defects and shallow draglines. As plate thickness was increased, fatigue resistance decreased for plasma cut holes, as should be expected. There was a noticeable difference in the initiation points between cut edges and cut holes, but the purpose of this literature review is to analyze the cut holes behavior. There was not a consistent fatigue response behavior for the different cutting processes across the various steel types. Overall, the study found that the fatigue detail category for plasma cut edges is a Category B, and for plasma cut holes is a Category E. For comparison, AASHTO defines drilled and punched holes to be Category D. The experimental study provided useful data using a large number of specimens to compare the fatigue behavior of plasma cut holes to the currently approved method of drilling holes.

Harris, I. (1997). *Plasma arc cutting of bridge steels* (NCHRP Report 384). Transportation Research Board.

The publication consisted of both a literature review and laboratory test to investigate the validity of thermal cut edges, specifically plasma cut, for bridge applications. The review also evaluated the effect of plasma cutting and subsequent welding of those edges. Parameters considered for the evaluation of plasma cutting included arc current, plasma gas used, and cutting speed. Parameters considered for the evaluation of the effect of welding include the presence of welding defects, heat input, and composition and microstructure of the plasma cut edges. As a result of the study, a User Guide was developed (Appendix A in the publication) to assist engineers, fabricators, and inspectors to use the processes outlined for plasma cutting steel plates in bridge applications.

At the time of publication, standards did not address the use of plasma cutting for plate edges or the edge treatment requirements, so the study was important in determining that plasma cutting is adequate for steel plate edges in bridge applications. More recently, plasma cutting is included in the codes as acceptable for cutting edges. The limitation of the publication is that it does not address plasma cutting for holes. The reason is that the focus of the publication was on plasma cutting in conjunction with welding, but our focus of our literature review is to evaluate plasma cut holes for bolted connections in bridges.

Lubitz, D. (2005). *Tensile and fatigue behavior of punched structural steel plates* [Doctoral Dissertation, University of Texas at Austin].

The two-part experimental study evaluated the performance of punched holes in tension as well as investigated the effects of bending on the ductility and fracture toughness of flange plates. Current AASHTO codes dictate that if punching is used for load-carrying members, the punched holes must be punched undersize and then reamed to full size. The focus was to determine the design requirements for cross frames and secondary members in tension where punching full size is utilized. Parameters that were evaluated in this study included plate thickness, strength of the plate, hole size, punch-to-die clearance, and temperature for both static and fatigue loading. Specimens were tested side by side comparing punched and drilled holes. Punched holes resulted in reduced strength and a reduction in ductility.

The researchers concluded that full punched holes should not be used in main load carrying members due to the reduction in ductility. Furthermore, while open holes are fatigue detail Category D, regardless of whether it is drilled or punched, it was concluded that punched holes with pretensioned high-strength bolts should be Category B (comparable to drilled holes). When bending a curved girder, heating should not be used in the bending process due to the formation of cracks correlating to the use of heat during bending. Additionally, the bending must be applied at a slow rate to prevent distortion and cracking.

The evaluation was thorough for secondary members and the utilization of punching full size holes. Limitations for our literature review are that we are focusing on main load carrying members and on plasma cut holes. Confirming that punched holes are sufficient for secondary members is helpful in confirming that plasma cutting should be adequate for secondary members as well.

Maljaars, J., & Euler, M. (2021). Fatigue S-N curves of bolts and bolted connections for application in civil engineering structures. International Journal of Fatigue, 151, 106355.

The journal article presents a meta-analysis evaluating thousands of fatigue tests previously performed in other studies. Findings of the study resulted in modifications to the European codes' fatigue classes and other parameters around fatigue performance. Selection for which previous studies were included was based on selecting studies that evaluated materials, manufacturing processes, and other parameters that the authors of this meta-study determined reasonably influenced the structural fatigue behavior.

The most pertinent conclusion related to our focus on plasma cut holes is that drilled and subpunched and reamed holes have higher fatigue resistance than that of thermally cut holes. The review of previous studies is thorough in information but limited in topics pertaining specifically to our focus.

Zampieri, P., Curtarello, A., Maiorana, E., & Pellegrino, C. (2019). A review of the fatigue strength of shear bolted connections. *International Journal of Steel Structures*, *19*, 1084–1098. https://doi.org/10.1007/s13296-018-0189-5

This publication is a literature review of experimental studies, numerical analysis, and the fatigue design rules for shear bolted connections with a focus on steel bridge applications. The article discusses the failure mechanism of fatigue cracking, parameters that influence the fatigue failure of bolted joints, and summarizes experimental studies carried out in the last fifty years. The report concludes with small-scale testing conclusions.

Failure via fatigue cracking begins with the crack initiation, which is influenced by geometry, stress magnitude, surface roughness, and environmental conditions. The crack propagates to an assumed observable size before the component finally ruptures. Failure in fatigue for bolted joints is strongly influenced by the parameters of the presence of defects introduced during the manufacturing process, as well as the stress concentration in the plates and parameters that lead to maximum stress values.

In the summarization of experimental studies carried out in the last fifty years, we observe valuable insights that may be pertinent to the research goals. Experimental studies have examined the influence of pretension, joint geometry, cyclic load types, and materials, surface treatments and hole cutting technology. Of most interest to the Purdue research team is the influence of pretension; the fatigue strength of preloaded bolts was slightly higher than that of the on-preloaded bolts.

Overall, previously conducted small-scale tests have not always evaluated the same parameters across different experimental studies, and thus can be difficult to compare the results across studies. Factors that emerged to have impact on the fatigue life of bolted joints include applied cyclic loading, surface roughness, cutting technologies, corrosion, etc. Unfortunately, results from existing research, particularly from small-scale tests, have not fully been incorporated in current standards, especially with regards to the influence that newer cutting technologies have on fatigue life. The goal is that large-scale testing will obtain conclusive results that can be incorporated into current codes and standards for future use in bridge applications.

AASHTO. (2017). AASHTO LRFD bridge construction specifications (4th ed.). American Association of State Highway and Transportation Officials.

The Bridge Construction Specification (BCS) is a specification used in the United States of America. The BCS discusses bolt holes in Article 11.4.8 and requires that all bolt holes shall be drilled or punched with a few exceptions as noted. Certain geometries require subdrilling or subpunching and reaming, but “where punching full size is permitted, holes may also be formed by plasma cutting …” Members that allow full size punched holes include fillers, cross frames, lateral bracing components, and the corresponding holes in connection plates between girders and cross frames or lateral components. Members that are not allowed to be full size punched include longitudinal main load carrying members, transverse floor beams, and any members designated as non-redundant steel tension members (NSTMs). For bridge applications, this eliminates many of the bridge main components.

RCSC. (2020). *Specification for structural joints using high-strength bolts*. Research Council on Structural Connections. https://www.boltcouncil.org/files/2020RCSCSpecification.pdf

The RCSC Specification is a standard used in steel construction in the United States of America. While there is no specific mention of plasma arc cutting in the RCSC Specification, there is discussion on thermally cut bolt holes in Section 3.3. For statically loaded joints, thermally cut holes are permitted under specified surface roughness requirements. However, for cyclically loaded joints, thermally cut holes are permitted only in slip-critical joints or as approved by the Engineer of Record (EOR) for other joints. For bridge applications, plasma arc cutting would require the approval of the EOR, but approval is not common due to the lack of data on fatigue performance of thermally cut holes.

AISC. (2023). *AISC steel construction manual, 16th Edition*. American Institute of Steel Construction.

The AISC Steel Construction manual is used in the United States of America. The AISC manual does permit thermally cut bolt holes under specified surface roughness requirements, but the specification is intended for structural steel buildings, not bridges.

BSI. (2018). *Execution of steel structures and aluminum structures–Technical requirements for steel structures* (BS EN 1090-2:2018). British Standard Institute. https://doi.org/10.3403/30320417

The British Standard (BS EN 1090-2:2018) is a European standard for steel construction. The BS EN 1090 dictates that generally fastener holes "may be formed by any process (e.g. drilling, punching, laser, plasma or other thermal cutting) provided that this leaves a finished hole such that…" it meets specified hardness, surface quality (Section 6,4), and assembly requirements. However, for our focus in bridge applications, the standard highlights a note that punching without subsequent reaming or subsequent drilling is not permitted in joints subject to cyclic (or seismic) loading. Additional requirements for the taper angle and burrs when using thermal cutting are outlined as well. As these are related to surface and cut quality, it makes sense that these requirements are added.

Joint Technical Committee BD-001. (2016). *Structural steelwork—Fabrication and erection* (Report No. AS/NZS 5131: 2016). Joint Standards Australia. https://www.standardsau.com/preview/AS%20NZS%205131-2016.pdf

The Structural Steelwork – Fabrication and Erection (AS.NZS 5131:2016) is the standard used in Australia and New Zealand for steel construction. The standard specifies that thermal cutting is generally acceptable as a cutting method for steel construction, unless otherwise excluded for a specific process as outlined in the standard. One possible reason plasma cutting may be deemed unacceptable is due to the maximum surface roughness requirements that are outlined for various loading applications, including fatigue loading. Section 6.7 discusses hole making for steel construction, where it dictates that “all holes shall be free from burrs and rough edges”. Although it does not say conclusively if plasma cutting is an acceptable method for hole making, the quality of the plasma cut hole would need to be evaluated for meeting the geometric and hole quality requirements.

CSA Group. (2019). *Design of steel structures* (CSA S16-19). Standards Council of Canada.

The Design of Steel Structures (CSA S16:19) is the Canadian standard used for steel construction. The standard outlines that thermally cut holes can be used in statically loaded structures if certain geometric requirements are met. There is no specific mention whether plasma cutting methods can be used for cyclically loaded applications.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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