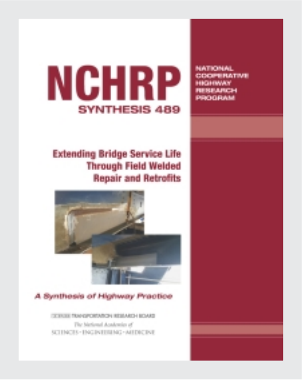

Extending Bridge Service Life Through Field Welded Repairs and Retrofits

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Expanding Bridge Service Life Through Field Welded Repair and Retrofits

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research is the most effective way to solve many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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Cover figure: Repair of beam ends due to corrosion and section loss. Provided by the Massachusetts Department of Transportation.

FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jo Allen Gause
Senior Program Officer
Transportation Research Board

This synthesis documents practices associated with field welded repairs on existing steel bridges used by bridge owners. The information presented includes the extent to which field welding is performed on existing bridges, common types of field welded repairs and retrofits, specifications, and quality control practices.

Information used in this study was gathered through a literature review and a survey of state departments of transportation. Follow-up interviews with selected agencies provided additional information.

Philip E. Fish and Curtis J. Schroeder, Fish & Associates, Inc., Middleton, Wisconsin, and Robert J. Connor, Purdue University, West Lafayette, Indiana, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable with the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

EXTENDING BRIDGE SERVICE LIFE THROUGH FIELD WELDED REPAIR AND RETROFITS

SUMMARY

The objective of this synthesis is to document practices and solutions associated with field welded repairs on existing steel bridges used by owners. The report is intended to help bridge owners evaluate and implement solutions for successfully extending the service life of their bridges. The information gathered for this synthesis included, but was not limited to, the extent to which field welding is performed on existing steel bridges, the common types of field welded repairs and retrofits, and manuals or specifications for field welded repairs and retrofits. Quality assurance and quality control practices are also investigated including welder qualifications and testing, material identification, welding procedure development and qualification, and verification inspection. Finally, the in-service performance of repairs and retrofits and effective practices are presented.

In the United States, welding on bridge structures was first implemented in the late 1940s and 1950s, but was primarily limited to highway bridge structures, not other bridge structures such as railroad bridges. During this time, bridge design and construction transitioned from members comprised of multiple components joined using mechanically fastened members (rivets or bolts) to a few elements joined using welds. Welding took place in fabrication shops and sometimes in the field, depending on how the bridge member and/or structure was designed and fabricated. Some agencies chose mechanical fasteners when members were joined together in the field, whereas others allowed field welding in lieu of mechanical fasteners. Field welding consisted of welding bridge girders at field splices, welding bracing in place, attaching bearings, etc.

With construction of the Interstate Highway System in the 1960s, numerous steel bridges were built that contained welded fatigue-prone details with limited consideration for fatigue compared with current standards. Field welding for the purposes of repair and retrofit is often performed as a repair strategy to mitigate cracks that occurred as a result of these various conditions. Repair and retrofit field welding has also been used to mitigate distortion-induced and out-of-plane fatigue cracking and to strengthen areas of section loss or a limited capacity rating. Although field welding has been used successfully by some agencies, it is still not widely implemented because of concerns regarding long-term performance, cost, or lack of knowledge and experience.

Information for this synthesis was obtained from three sources:

1. A literature review was performed to provide background information on the state of practice of field welding for repair and retrofit and to uncover previous research that was performed on this topic.
2. A survey was distributed to voting members of the AASHTO Subcommittee on Bridges and Structures (SCOBS) requesting information on their field welding practices. A total of 43 state departments of transportation (DOTs) responded to the survey, an 86% response rate.
3. Telephone interviews with representatives from six DOTs were conducted to acquire additional information on effective practices and specific field welding projects, which are used as case examples.

The six DOTs that were selected for the phone interviews were chosen based on several factors, including an expressed willingness to provide additional information; details on their specific field welded project(s) including type of damage, type of bridge, and type of bridge member; and varied geographic locations.

The literature review found that field welding presents special challenges when compared with original shop fabrication. Concerns regarding overhead positioning of many field welding repairs were raised in multiple sources. Another of these challenges is the weldability of the steel, because it may be of unknown composition. The American National Standards Institute (ANSI)/American Welding Society (AWS) defines weldability as the capacity of material to be welded under the imposed fabrication conditions into a specific, suitably designed structure performing satisfactorily in the intended service. Any adverse fabrication conditions present in the field must be accounted for during a determination of the weldability of a material for field welding. Field welded repairs and retrofits will also likely involve welding of steels that have ASTM specifications that are out of date compared with current specified bridge steels. Of the 43 state DOT survey respondents, 32 (74%) noted that their agency allows for planned field welded repairs and retrofits to be performed. Of the 11 agencies (26.6%) that do not allow planned field welded repairs and retrofits, two have previously done field welding. The remaining nine agencies have never done field welding and do not currently allow it. States as far north as Alaska, North Dakota, Minnesota, and Maine allow field welding, and overall, there does not appear to be a correlation between lowest anticipated temperatures and general geographic location and the propensity for field welding.

The survey results determined that two primary welding codes are used for the structural welding of steel structures in the United States: AWS Bridge Welding Code D1.5 and AWS Structural Welding Code D1.1. AASHTO/AWS Bridge Welding Code D1.5 is the welding code required for new fabrication of bridges by the AASHTO bridge design specification. AWS Structural Welding Code D1.1 is the welding code that is required for fabrication of buildings and other structures. The specific welding code to be applied to bridge field welding may vary from state to state.

Various state DOT manuals that cover field welding were reviewed to determine any aspects that are typically included in these manuals. In general, welder qualification programs are instituted by each state DOT in which the welder qualification tests are conducted or witnessed by state representatives. Records of field welders who have successfully passed the qualification test are entered into the department’s database.

The literature review revealed that one of the greatest concerns of field welding is the quality. Field welding requires the same quality control measures as shop welding; however, quality control is more difficult to maintain under field conditions. As discovered during the literature review, this concern was expressed in multiple references. One report stated that the inspection of repair welds is to be at least as thorough as when the bridge was originally fabricated. This includes matching the current requirements for the methods and extent of the inspection compared with current bridge fabrication practices. According to the same report, visual welding inspection is the most important inspection method and is used on all repair welds, independent of the utilization of any other inspection methods. Welding inspectors are typically provided with the repair procedure and details, drawings or sketches, and acceptance criteria. Visual inspection is performed before, during, and after welding.

The agencies surveyed for the case examples stress the importance of good inspection by qualified people. Each of these agencies perform visual inspection in-house by a Certified Weld Inspector or an experienced individual. Nondestructive testing (NDT) varied; some agencies contracted all testing out, whereas others performed a portion of the testing in-house and/or contracted the remainder out.

Agencies surveyed emphasized the importance of quality welders. The ability of a welder to produce a weld of acceptable quality can be verified through the use of welder performance qualification tests specified in the applicable welding code. The qualification is typically indefinite provided that the welder carries out similar work within a certain time period. However, this may vary depending on specific agency requirements. The agencies interviewed for the case examples often require additional welder qualification tests.

The agencies surveyed for the case examples all stressed the importance of good procedures and proper qualifications. They required field procedures, welder qualifications, inspection procedures, visual and NDT inspector qualifications, and emphasized the importance of following the inspection requirements.

Most of the agencies surveyed reported good results from field welded repairs. Agencies were asked whether there have been any major problems associated with the field welded repairs and retrofits. This question was put to all agencies that answered that they either allow planned field welded repairs and retrofits or have performed them previously, a total of 34 agencies. Twenty-four of the 34 agencies responded that there have been no major problems associated with repairs and retrofits specifically because they were field welds. Six agencies reported that it was not known whether there have been any major problems specifically because they were field welds and agencies that they *have* had major problems specifically because they were field welds.

The most common issue with field welding among the small number of agencies that reported having major problems was premature cracking, which was selected by three of the four agencies. Improper welding and quality workmanship issues were the next most common, selected by two of the four agencies. Installation not in accordance with the plans and specifications was selected by one agency.

All six agencies surveyed for the case examples reported good results from the welded repairs. Each of these agencies endorses the use of field repair welding and plan on continuing to do such repairs. They also reported that field welding is an economical repair method.

The synthesis revealed that many agencies identified a lack of experienced inspectors and/or a lack of qualified agency supervisors or administrators to allow field welded repairs and retrofits in their program.

The results of the synthesis identified the following gaps in current knowledge that could be addressed by further research activities:

- Identifying the effective practices performed by the states that have used field welding successfully;
- The second activity is monitoring actual field welded repairs; and
- Recording data on how the fatigue life of the repair is influenced by the environment, vibration, dead load and live load stresses, and quality.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Prior to World War II, individual components of bridges in the United States were connected using mechanical fasteners, primarily rivets. During the war, welding became more pronounced in the fabrication of members owing to improvements in welding equipment, knowledge regarding the process, and welding applications to support the war effort. The significant transition to welded bridge structures took place post-World War II.

Welding on bridges was introduced as early as 1934, when the first all-welded bridge was built in Middlesbrough, England (Sapp 2015). In 1936, the first specification for Design, Construction, Alteration and Repair of Highway and Railway Bridges was issued by the American Welding Society (AWS) (Sapp 2015).

Welding on bridges in the United States was implemented in the late 1940s and 1950s, but was primarily limited to highway structures. During this time, bridge design and construction transitioned from members comprised of multiple components joined using mechanically fastened members (rivets or bolts) to fewer elements joined using welds. Welding took place in fabrication shops and sometimes in the field, depending on how the bridge member and/or structure was designed and fabricated. Some agencies required that mechanical fasteners be used when members were joined together in the field, whereas others allowed field welding in lieu of mechanical fasteners. Field welding included, for example, welding bridge girders at field splices, welding bracing in place, and attaching bearings.

The transition from built-up, mechanical fastened members and connections to all welded members and connections led to issues with fatigue and fracture. Often, the same types of connection details were used, except that welds were substituted for mechanical fasteners. Because of the increased stiffness associated with welded joints, typically lower fatigue resistance, and general lack of understanding regarding fatigue of welded joints, unexpected cracking was observed. With construction of the Interstate Highway System in the 1960s, numerous steel bridges were built containing welded fatigue-prone details, with limited consideration for fatigue compared with current standards. As a result of the observed cracking during the AASHO Road Test and on several in-service bridges, considerable research was funded by NCHRP in the 1970s to study the effect of cyclic loading on the fatigue performance of welded connections (Fenves et al. 2005). As a result, design requirements were revised to include consideration for fatigue in welded connections for shop and field welding.

Field welding on bridges began to occur more frequently in the early 1960s and into the 1970s. During this time, steel bridges were designed with a goal of assembling bridges in the field without the use of permanent bolts. Girders were prefabricated in a shop and delivered to the construction site for erection. In many cases, the only bolts needed were the erection bolts to help secure in place the various components such as girders and bracing. Once erected, the girders were temporarily supported so that field splices on the girders could be field welded in the erected position. In general, these were intended to be complete joint penetration (CJP) groove welds that included the webs, top flanges, and bottom flanges. The bracing systems, both vertical and lateral bracing, were connected with field welds, often fillet welds. Field welding differs from shop welding for two main reasons: (1) the welding environment is not as controlled, and (2) the steel to be welded cannot be manipulated into position as easily as in the shop. Some of the in-service issues of field weld cracking and field weld failure could possibly be attributed to a lack of welding knowledge, inadequate knowledge of fatigue details, poor quality work, lack of nondestructive testing (NDT) to identify initial defects, and a lack of quality oversight. At this time, CJP welds were not often ground smooth, and there was no type of weld-access holes between the web and flange of the girders. Because of the field conditions, there was often a significant misalignment of members and, as mentioned previously, the erection bolt holes were often plug welded with poor quality welds.

Field welding for the purposes of repair and retrofit is often performed as a repair strategy to mitigate cracks that occurred as a result of these varied conditions. Repair and retrofit field welding has also been used to mitigate distortion-induced and out-of-plane fatigue cracking, and to strengthen areas of section loss or a limited capacity rating. Although field welding has been used successfully by some agencies, it is still not widely implemented because of concerns (both substantiated and unsubstantiated) regarding long-term performance, cost, or a lack of knowledge and experience.

Agencies that allow field welding find that it is an effective tool for completing repairs within a short time. A design can be developed quickly along with a simple set of specifications, and base material can be ordered to the required size. Concurrently, welding procedures, required welder qualifications, acquisition appropriate weld metal, and access equipment needs can all be identified. When properly executed, a high-quality repair can be undertaken in a minimal amount of time with less disruption to the traveling public.

SYNTHESIS OBJECTIVES

The objective of this synthesis is to document planned field welded repair and retrofit solutions and practices that owners have used on existing steel bridges. The information contained in this document is intended to help bridge owners evaluate and implement solutions for successfully extending the service life of their bridges.

SYNTHESIS SCOPE AND APPROACH

This synthesis addresses various aspects of projects where field welding is being considered. The emphasis of this synthesis is planned field welded repairs and retrofits where consideration was given to design, specifications, procedures, qualifications, and inspection requirements before performing work. Information has been collected regarding when to implement this technique; current related manuals, codes, and specifications; quality assurance and quality control practices; performance of field welded repairs and retrofits; and effective practices for field welding.

This synthesis presents current practice in the following specific areas:

- General information on field welding internal policies and practices of each agency surveyed; whether they allow field welding currently, allowed it previously, or will not allow field welded repairs and retrofits on their bridges.
- The agencies that have standard field welding plans, specifications, procedures, or details and the frequency of field welded projects that have plans or specifications prepared before field welding is performed.
- The typical requirements for characterizing the chemistry and grade of the base metal, as well as the typical techniques used to verify weldability of the base material.
- How often governing specifications and welding codes are specified for field welded projects and the typical welding codes used for field welding.
- Types of field welded repairs and retrofits and the frequency of each type.
- Information on the typical field welding design and welding staff, including whether the welders are from internal staff or outside contractors and whether the welders are certified according to the requirements of the applicable welding code.
- The typical quality assurance and quality control practices including welder qualifications and qualification programs, welding procedure development and qualification, inspection requirements and procedures, and inspector qualifications.
- The in-service performance of field welded repairs and retrofits including the number of agencies that have had projects with major problems and the typical problems that occur.
- The effective practices and lessons learned by agencies that have performed field welded repairs and retrofits.

Information for this synthesis was obtained from three sources.

1. A literature review was performed to provide background information on the state of practice of field welding for repair and retrofit and previous research that was performed on this topic.
2. A survey was distributed to voting members of the AASHTO Subcommittee on Bridges and Structures (SCOBS) for each of the 50 states and the District of Columbia requesting information on their field welding practices. A total of 43 states (86%) responded to the survey.
3. Finally, telephone interviews with representatives from six departments of transportation (DOTs) were conducted to acquire additional information on effective practices and lessons learned, along with information on specific field welding projects, which are used as case examples.

These six DOTs were chosen based on several factors, including an expressed willingness to provide additional information; details on their specific field welded project(s) including type of damage, type of bridge, and type of bridge member; and varied geographic location.

SYNTHESIS ORGANIZATION

This synthesis is organized into five chapters:

- Chapter one introduces the synthesis, providing background information and summarizing the scope and organization of the document.
- Chapter two presents and summarizes the findings from the literature review.
- Chapter three presents the results of the survey of the state of the practice. The results are presented in the following topic areas:
  - Extent of field welding,
  - Current manual and specifications,

  - Quality assurance and quality control, and
  - Performance of repairs and retrofits.
- Chapter four summarizes the information provided by the six agencies that were interviewed for the case examples. The results are presented in the following topic areas:
  - Extent of field welding,
  - Current manual and specifications,
  - Quality assurance and quality control,
  - Performance of repairs and retrofits, and
  - Effective practices and lessons learned.
- Chapter five concludes the reports with a summary of key observations from the findings and suggestions for further research and outreach in field welding.
- Three appendices are included: Appendix A provides links to the responding DOT agencies, Appendix B provides a copy of the questionnaire that was distributed electronically to the state participants, and Appendix C presents the responses by state for each of the questions posed to the survey participants. All appendices are available in the online version of the report.

CHAPTER TWO

LITERATURE REVIEW

INTRODUCTION

The literature review process began with a search of the Transport Research Information Database (TRID) for documents related to field welding of highway bridges. The keywords and phrases that were searched included "field welding," "field weld," and "repair weld." Additional Internet searching was performed to find documentation from individual transportation agencies on field welding practices. The bridge and structural welding codes were also reviewed for any additional information or references. It was found that there is limited published research or literature on the topic of field welding and field repair welds.

OVERVIEW

Field welding is welding of a material outside of a fabrication shop. Field welding typically occurs at the bridge site. The emphasis of this synthesis is on planned field welded repairs and retrofits where consideration was given to design, specifications, procedures, qualifications, and inspection requirements considered before performing work.

EXTENT OF FIELD WELDING

There is limited literature on the extent of field welding performed on steel bridges. Only one research document was found that specifically talked about the amount of field welding performed in the bridge industry; *NCHRP Report 321* (Gregory et al. 1989) found that most states would use welding as a repair method if it was proven in advance to be successful and if guidance was available on the subjects of inspection and quality control. They also reported that only one bridge owner claimed that they would never use welding for repair of cracks. According to this report, the agency's confidence appeared to be the key to repair welding because "Those states that did not like to weld in the field all stated that it was impossible to obtain welding and inspection personnel of a sufficiently high standard to produce a sound welded repair" (Gregory et al. 1989).

Types of Field Welded Repairs

The literature review revealed that field welded repairs are performed on structures for three primary reasons: fatigue improvement, capacity strengthening, and corrosion and impact damage repairs or retrofits.

Fatigue Improvement

This typically includes retrofit of out-of-plane and distortion-induced cracking by welding the connection stiffener to the flange. In most cases, the welding is on the tension flange. Welding of the transverse stiffeners and cross-brace connection plates to the tension flange was avoided prior to the early to mid-1980s because of concerns over fatigue cracking or brittle fracture of the tension flange (Zhao and Roddis 2004; Connor and Fisher 2007). As a result, a rigid connection between the girder flange and web-mounted stiffeners and connection plates was generally not provided. The lack of a positive connection often resulted in cracking from out-of-plane distortions, as shown in Figure 1, in a plane parallel to the primary loading stress (Zhao and Roddis 2004).

In hindsight, not welding the connection plate to the tension flange led to out-of-plane cracking of the web within the small web gap between the web-to-flange weld and termination of the connection plate to web fillet weld, as shown in Figure 2 (Fish et al. 2015). At present, the current AASHTO LRFD design provisions (AASHTO 2014) require that the connection plate be welded or bolted to both the compression and tension flanges to resist out-of-plane cracking. Stiffening of the web gap by welding the connection plate to the tension flange is one of many common retrofit endorsements (Zhao and Roddis 2004).

This retrofit strategy is simpler than a bolted retrofit; however, it requires that the connection plate extend completely to the tension flange. Because the connection plates were often trimmed short of the tension flange, another plate may be required to be attached to the stiffener, which is then welded to the flange. This retrofit strategy also requires that the stress ranges in the flange not exceed the limits given by AASHTO Fatigue Detail Category C, which is the applicable detail category. If present, existing cracked welds are typically gouged out before the new welds are applied. It is important that finish grinding be performed after completion of welding to provide a smooth final surface. The use of field welding to repair out-of-plane and distortion-induced cracking is often not recommended by many DOTs as a result of the expensive labor necessary to ensure good weld quality and smooth surface grinding, along with the fear of introducing another

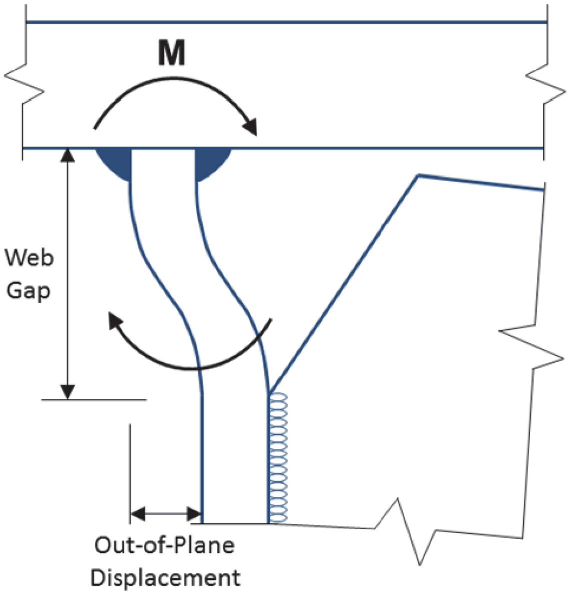


FIGURE 1 Out-of-plane and distortion-induced cracking in web gap (adapted from Fisher and Keating 1989).

fatigue-sensitive detail in a primary load carrying member. Therefore, this method is often the last choice when other repair methods are not effective at stopping crack growth (Zhao and Roddis 2004; Hu et al. 2006). Hu et al. (2006) noted that the use of field welding to repair out-of-plane cracking, while convenient, should be minimized as a result of several potential problems. This includes overhead welding position, extensive cleaning to remove corrosion and dirt buildup, and preheat requirements that may be difficult with the large concrete mass above the top flange.

FIGURE 2 Out-of-plane and distortion-induced cracking (Snyder 2015).

In the 1970s, Fisher et al. studied the use of gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, to remelt the metal at the weld toe to improve the fatigue resistance. This method was only validated using cover plate termination details. In this process, a small volume of fillet weld and base metal is remelted by manually moving the tungsten electrode along the weld toe. This process can be used to improve the fatigue resistance at uncracked weld toes and to melt the volume containing existing shallow surface cracks to fully remove the crack. This research is documented in *NCHRP Report 206* (Fisher et al. 1979).

Capacity Strengthening

This process typically involves a retrofit to increase capacity resulting from a poor load rating such as adding stiffeners to increase shear resistance. These repairs are undertaken in cases where the members were designed to support a lighter load than required under current specifications and are distinguished from those where damage of some kind exists.

Corrosion and Impact Damage Strengthening

This includes repair or retrofit of damaged members. These members may have corrosion damage that has resulted in significant section loss and either requires additional stiffening or complete replacement of the member. Corrosion is typically repaired with the addition of reinforcing material or section replacement (Gregory et al. 1989). Impact damage frequently results in distorted and damaged members, which may also include cracking or tearing of the bridge member. Repair of impact damage normally involves straightening, with some welding or bolting of new or additional material (Gregory et al. 1989; Connor et al. 2008).

NCHRP Report 321 (Gregory et al. 1989) found that the rate of the occurrence of these damage types varied from state to state. In some states, corrosion was the major problem with steel bridges, whereas others had major problems with accident damage and fatigue cracking.

Field Welding Design Considerations

Field welding presents special challenges when compared with original shop fabrication. Concerns regarding overhead positioning of many field welding repairs were raised in multiple sources (Miller 1993; Zhao and Roddis 2004; Hu et al. 2006). Another challenge is the weldability of the steel, because it may be of unknown composition. According to ANSI/AWS A3.0-2010, weldability is defined as the capacity of material to be welded under the imposed fabrication conditions into a specific, suitably designed structure performing satisfactorily in the intended service. Therefore, the weldability of a material for field welding must account for any adverse fabrication conditions that are often present in the field.

Field welded repairs and retrofits will likely involve the welding of types of steels where the ASTM specifications are out of date compared with current specified bridge steels; therefore, the current welding codes may not account for special requirements of these steels. When the composition of the steel is unknown or in doubt, it is necessary that analysis be performed so that a welding engineer can determine whether it is suitable for welding. It is imperative to know the chemical composition of the steel being joined (Miller 1993).

Weld-access holes are used to provide access for repair welds in the flange of a girder and are placed in the web of the girder at the weld location. It is important that weld-access holes have adequate space to allow the welder to produce a good quality weld in this region. Run-off tabs and backing bars are utilized in welds requiring a CJP weld because this will help to eliminate the lack of penetration or lack of fusion from the welds. Generally run-off tabs and backing bars are taken off by grinding to remove any stress concentrations and to aid in inspection.

Adverse fabrication conditions in the field include a susceptibility to cracking when the steel base material is under high restraint. The rigidity of the structure or member does not allow for movement derived from shrinkage of the weld, which results in large shrinkage or residual stresses in the weld metal. Under conditions of high restraint, the likelihood of hydrogen cracks also increases, generally in the weld metal. This type of cracking may occur up to several hours after welding has been completed because the hydrogen in the weld metal will diffuse into the heat affected zone (HAZ) when the weld cools. Adequate preheat and welding sequences are the critical components to resisting weld cracking resulting from shrinkage stresses by slowing down the cooling rate and limiting the restraint. Other factors that affect hydrogen cracking are the thickness of the material and the type of joint because this influences the degree of restraint, the composition of the steel, and the hydrogen content of the weld metal. The use of low hydrogen electrodes, which are dried at high temperatures before welding, can also aid in the prevention of hydrogen cracking.

NCHRP Report 321 (Gregory et al. 1989) identified effective field welding practices that can be used to improve the welded repair of cracks in steel members. It can be noted that this research was initiated before the publication of the first edition of the AASHTO/AWS D1.5 Bridge Welding Code. Therefore, any requirements in AASHTO/AWS D1.5 will take precedent over recommendations in this report.

NCHRP Report 321 recommended the following:

- Because of the high levels of restraint typically present during field welded repairs and retrofits, minimum preheat temperatures of no less than 250°F should be used except when the steels are of quenched and tempered types.
  - For quenched and tempered steels such as ASTM A514 and A517, a separate table for minimum and maximum preheat temperatures is provided. Overheating owing to high preheat and interpass temperatures and high heat input can possibly reduce the specified tensile and yield strengths, along with toughness.
  - The recommended minimum preheat temperature for ASTM A7 steel when carbon content is below 0.4% was 350°F. Because carbon content was not specified for ASTM A7 steels, a lower preheat and interpass temperature may be used for lower carbon contents.
- Whenever possible, preheating should be maintained throughout the duration of the repair.
- A preheating temperature of 100°F below the recommended preheat and interpass temperatures could be used before air-carbon arc gouging.
- To reduce the chance for delayed hydrogen cracking, steels with carbon content of greater than 0.4% may require additional heating immediately after welding is completed to maintain an elevated temperature for an extended period of time.
- Whenever possible, chemical or spectrographic analysis of a drilling or piece of steel should be performed even if the specification of the steel is known or mill test reports are available, because the steel may have been supplied out of specification or incorrect mill reports may have been supplied. This report included two tables for the tensile and chemical properties of the most commonly used steels in bridge construction over the previous 50 years before the publication of the report. This list does not include current ASTM specifications for bridge steels such as ASTM A709.

CURRENT MANUALS AND SPECIFICATIONS FOR FIELD WELDING

Two primary welding codes are used for structural welding of steel structures in the United States: AWS Bridge Welding Code D1.5 (AASHTO/AWS 2010) and AWS Structural Welding Code D1.1 (AWS 2010b). AWS Bridge Welding Code D1.5 is required for new fabrication of bridges by the AASHTO bridge design specification. AWS Structural Welding Code D1.1 is required for fabrication of buildings and other structures. The specific welding code to be applied to bridge field welding may vary from state to state. Each welding code contains requirements for the design of welds, qualification of welders and welding procedures, qualification of inspectors, and inspection and workmanship requirements.

AWS Bridge Welding Code D1.5:2010 does not make a distinction between shop and field welds and does not contain any additional requirements for the strengthening and repairing of existing structures. When this code is specified on a field welding project, it is implied by the engineer that all of the code requirements for shop welds are also required for field welding including quality control requirements, having qualified welding operators, written and qualified welding procedures, and workmanship requirements.

AWS Structural Welding Code D1.1:2010, Section 8, on the other hand, includes additional requirements and guidance for field welding on existing structures. This section, "Strengthening and Repairing Existing Structures," is quite brief, with only one and one-half pages of dialog. All of the requirements for shop welding elsewhere in the code apply to field welding on existing structures, along with the additional requirements in Section 8, which cover base metal, design of repairs and retrofits, fatigue life enhancements, workmanship and technique, and quality.

AWS has published a guidance document for the strengthening and repair of existing structures as AWS D1.7, *Guide for Strengthening and Repairing Existing Structures* (AWS 2010). Although this document is not a prescriptive code and does not include acceptance criteria, it does contain a considerable amount of useful information on what to consider before performing a field welded repair. This document contains extensive discussion on weldability of steel, including descriptions of the common classifications of structural steel, various carbon equivalency equations, and common alloying elements. It also includes discussion on the means for determining an alternate acceptance criteria for discontinuities found on existing structures that do not meet the current fabrication codes.

The qualified welding procedure has to meet the requirements of the specified welding code and is based on mechanical and nondestructive test results of weldments. According to AWS D1.1 Structural Welding Code and AASHTO/AWS D1.5 Bridge Welding Code, welding procedures must be properly documented in a written format. This format, called a Welding Procedure Specification (WPS), may either be prequalified if all requirements for prequalification in the applicable welding code are met or may be qualified by testing in accordance with the requirements of the applicable code. Even if a WPS is prequalified, it must still be written and available to those authorized to use or examine them. In D1.5 Bridge Welding Code all procedures, except shielded metal arc welding (SMAW) that utilizes filler metals with a minimum specified yield strength less than or equal to 90 ksi, must be qualified by testing. In D1.1 Structural Welding Code, SMAW; submerged arc welding; gas metal arch welding, except short circuit transfer mode; and flux cored arc welding processes may be prequalified if they meet the specified requirements.

If the actual parameters of the field welding differ from the prequalification requirements, the procedures must be qualified through testing. A written Procedure Qualification Record is required under the AWS D1.1 and D1.5 welding codes to qualify a WPS through testing. The main parameters that are typically verified for accuracy are minimum preheat temperature, minimum interpass temperature, welding current, voltage, travel speed, proper protection of filler metals, and appropriate welding techniques. The current, voltage, travel speed, and technique used to deposit the weld metal will control the heat input from welding that can affect the toughness of the base material, weld metal, and HAZ if it is not kept within acceptable limits.

The ability of a welder to produce a weld of acceptable quality is verified through the use of welder performance qualification tests. Typically, the qualification lasts indefinitely provided that the welder carries out similar work in a certain time period without interruptions. However, this requirement may vary depending on specific agency requirements.

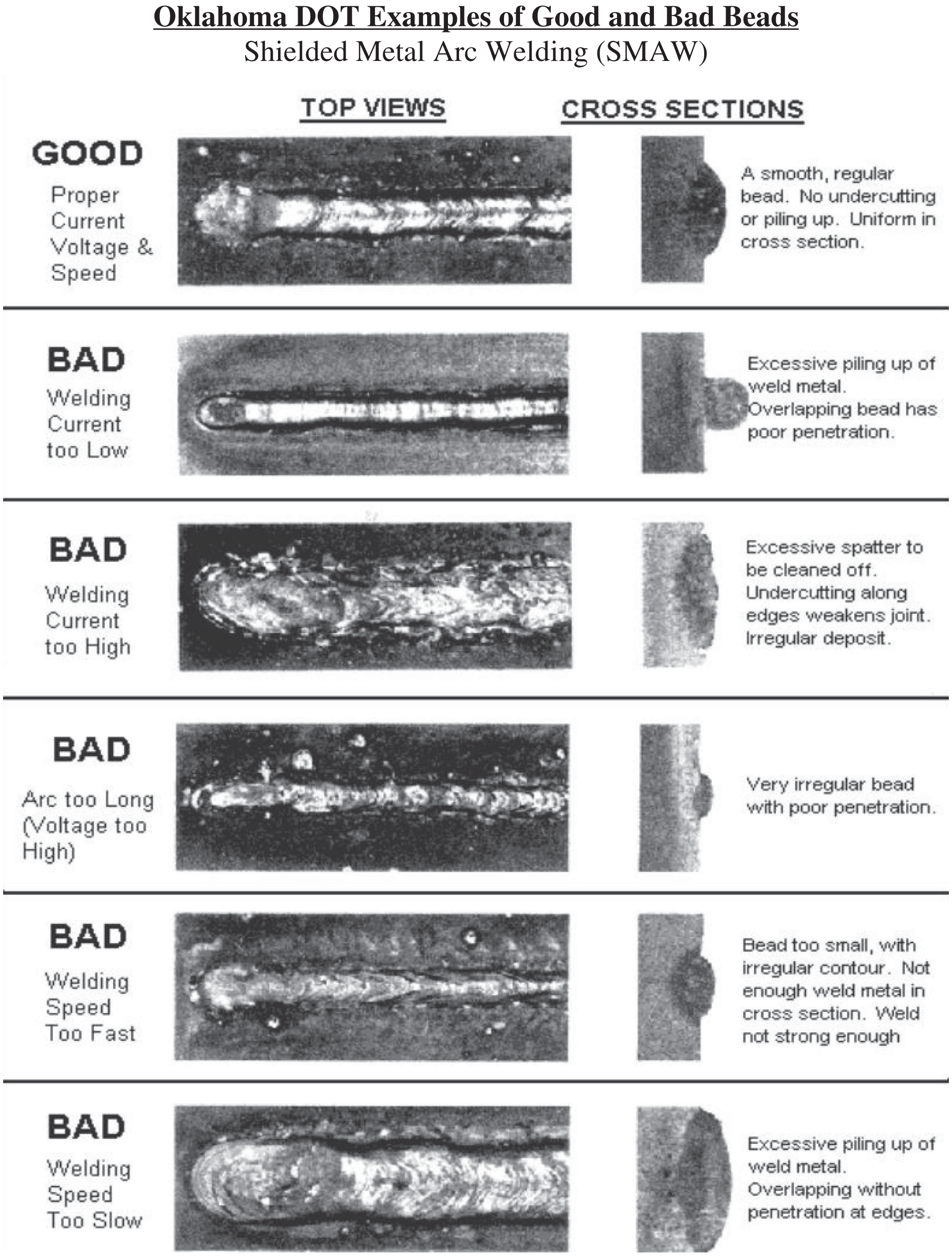
Various state DOT manuals that cover field welding were reviewed to determine any aspects that are commonly included in state manuals. Welder qualification requirements were included in the Iowa (Iowa DOT Office of Materials 2011), North Carolina (North Carolina DOT Materials and Tests Unit 2006), New York (New York Office of Structures 2008), Ohio (Ohio Department of Transportation 2008), Oklahoma (Oklahoma DOT Materials & Research Division 2012), and Texas (Texas Department of Transportation 2004) DOT state manuals. Generally, welder qualification programs are instituted by each state DOT where the welder qualification tests are conducted or witnessed by state representatives and a record of field welders who have successfully passed the qualification test are entered into the department's database. These DOTs require that all personnel performing field welding on their construction project pass the welder qualification process and be documented as qualified welders. In AWS D1.5, the welder must be qualified for the position in which they will weld, and a table was developed that lists the qualified positions for each test position.

Oklahoma DOT requires that all bridge welders test on a fillet weld assembly in the vertical (3F) and overhead (4F) positions, along with groove weld assemblies in the horizontal (2G), vertical (3G), and overhead (4G) positions (Oklahoma DOT Materials & Research Division 2012). North Carolina DOT requirements are very similar to Oklahoma DOT except they do not require the horizontal (2G) position (North Carolina DOT Materials and Tests Unit 2006). Texas DOT requires that bridge welders who perform groove welding pass the qualification test for groove welds for plates in the vertical (3G) and overhead (4G) positions along with other additional requirements (Texas Department of Transportation 2004). New York DOT requires that bridge welders who perform groove welding pass the qualification test using either the vertical (3G) and/or overhead (4G) positions depending on the project required positions (New York Office of Structures 2008). The Oklahoma, North Carolina, and Texas DOT requirements are tougher than the requirements in AASHTO/AWS D1.5. Iowa DOT includes the same table for the qualified positions as AASHTO/AWS D1.5 (Iowa DOT Office of Materials 2011), and the Ohio DOT manual states that the welders must be qualified for the position in which they are welding (Ohio Department of Transportation 2008).

It was also found that many of the state agencies had field welding inspection guides that included information to aid weld inspectors. This includes, but is not limited to, information on the typical weld symbols, welding procedures, electrodes and electrode storage, preheat and interpass temperatures, weld joint preparation and cleaning, weld inspections, equipment, and typical weld discontinuities. An example of good and bad weld beads from Oklahoma DOT is shown in Figure 3.

QUALITY CONTROL AND QUALITY ASSURANCE

One of the greatest concerns is the quality of the field welds. Field welding requires the same quality control as shop welding; however, quality control is more difficult to maintain under field conditions. During the literature review, this concern was expressed in multiple references (Gregory et al. 1989; Miller 1993; Keating et al. 1996; Zhao and Roddis 2004).



GOOD Proper Current Voltage & Speed	A smooth, regular bead. No undercutting or piling up. Uniform in cross section.
BAD Welding Current too Low	Excessive piling up of weld metal. Overlapping bead has poor penetration.
BAD Welding Current too High	Excessive spatter to be cleaned off. Undercutting along edges weakens joint. Irregular deposit.
BAD Arc too Long (Voltage too High)	Very irregular bead with poor penetration.
BAD Welding Speed Too Fast	Bead too small, with irregular contour. Not enough weld metal in cross section. Weld not strong enough
BAD Welding Speed Too Slow	Excessive piling up of weld metal. Overlapping without penetration at edges.

FIGURE 3 Oklahoma DOT weld quality examples (Oklahoma DOT Materials & Research Division 2004).

This does not imply that the quality or quality control requirements are different for field welds than for shop welding. It simply means that it can be more difficult to maintain quality control under field conditions. The control of field welded repairs often relies heavily on the competency of the contractor performing this work. Engineers tend to rely on the contractor's expertise, experience, and reputation to ensure quality workmanship. Even with an experienced contractor, the engineer and quality assurance inspectors must ensure that they responsibly perform their duties.

Welder Qualification

According to the AWS D1.1 and 1.5 welding codes, welding should only be permitted by individuals who have passed the appropriate qualification tests in accordance with the provisions of the specified code. According to *NCHRP Report 321* (Gregory et al. 1989), the WPS and any applicable Procedure Qualification Record should be subject to the approval of the Engineer of Record for the repair welding before the welding is conducted. This report goes on to state that a simple test, such as the fillet weld break test, may be required when the quality of the welder's work does not appear to be up to the required standard. This report also advised that the welder carry out a practice repair weld at the actual site of the repair that duplicates the conditions that will be encountered. It is important that this rehearsal of the repair include appropriate plate thickness and arrangement of the plates to reproduce the access available on the actual bridge. The practice repair provides an opportunity to verify that the welder is sufficiently prepared and that the equipment is adjusted properly before beginning the bridge welding. The rehearsal repair could include mock-up cracks marked on the plates and any preheat, removal, and post-heat requirements. These welds can be evaluated using NDT to verify their quality before the actual repair welding is initiated. In addition, mechanical properties may be required for welding on a fracture critical member (FCM).

Weld Inspection

It is important that the inspection of repair welds be at least as thorough as when the bridge was originally fabricated (Gregory et al. 1989). This includes matching the current requirements for the methods and extent of the inspection compared with current bridge fabrication practices. Acceptance requirements for visual and NDT of the welds are included in the AWS welding codes and, typically, the requirements for AWS D1.1 or AASHTO/AWS D1.5 will be specified for each project. The acceptance criteria in the AASHTO/AWS welding codes include the size and distribution of welding discontinuities that are either permissible or rejectable. The requirements in AWS D1.1 may be modified by the engineer through the project specifications and any additional requirements can be specified. Although unlikely, the engineer may also decide to use a fitness-for-service approach to specify the acceptance criteria of field welds. Typically, the requirements of BS 7910 (British Standards 2013) or API 579 (American Petroleum Institute 2007) are applied to a fitness-for-service evaluation of steel structures.

AWS D1.1 and D1.5 welding codes require that welding inspectors be suitably qualified to one of the following standards and that this qualification be documented by:

- Current or previous certification as an AWS Certified Weld Inspector (CWI) in conformance with the provisions of AWS QC1, Standard for AWS Certification of Welding Inspectors.
- Current or previous qualification by the Canadian Welding Bureau in conformance with the requirements of the Canadian Standard Association Standard W178.2, Certification of Welding Inspectors.
- An individual who, by training or experience, or both, in metals fabrication, inspection, and testing, is competent to perform inspection of the work.

Visual testing welding inspection is the most important examination method and is applied to all repair welds, independent of the utilization of any other inspection methods (Gregory et al. 1989). Welding inspectors are provided with the repair procedure and details, drawings or sketches, and acceptance criteria. Visual inspection is typically performed before welding, during welding, and after welding.

Before welding, visual inspection includes confirmation of groove dimensions, cleanliness and surface finish of the groove, removal of any existing weld discontinuities, fit-up of plates, and fit-up of backing bars (if present). During welding, visual inspection includes confirmation of preheat and interpass temperatures, welding sequence, electrode requirements, storage and handling, welding variables, and post-weld heat treatment. After welding, visual inspection includes confirmation of backing bar removal, surface finish, size of welds, and lack of rejectable weld discontinuities.

Typical NDT methods applied to field welded repairs and retrofits include:

- Dye penetrant testing (PT),
- Magnetic particle testing (MT),
- Ultrasonic testing (UT), and
- Radiographic testing (RT).

PT is a convenient and simple NDT method that is limited to inspection of surface discontinuities. High or low temperatures can affect the results of PT; therefore, *NCHRP Report 321* advised against using this method when the steel temperature range is not within 40°F–110°F (Gregory et al. 1989).

MT is limited to inspection of surface or near surface discontinuities in ferromagnetic materials. This method can be slightly more sensitive to tightly closed cracks; however, it can be more time consuming and requires more skill to differentiate actual discontinuities from false calls. MT can be affected by wind.

Both UT and RT can be used to inspect for internal discontinuities. These methods require advanced training to properly perform the inspection and evaluate the results.

Radiography in the field can have issues resulting from safety concerns and portability. Large thicknesses may require different sources that may be less portable than iridium sources that can be used on thinner material. UT can also be affected by temperature because the couplant can either dry out if the steel is very hot or freeze if the steel is too cold.

The AWS D1.1 and D1.5 welding codes require that personnel performing NDT other than visual be qualified in accordance with the current edition of the American Society for Nondestructive Testing, *Recommended Practice Number SNT-TC-1A* as NDT Level II or as NDT Level I working under the NDT Level II.

Welding Cleanliness

Adequate cleaning of the field weld location to remove paint, galvanizing, dirt, loose or thick scale, slag, rust, moisture, grease, or other impurities is required by the AWS welding codes. Scaling rust, pits, or other surface irregularities can affect both the welding and subsequent NDT. Oklahoma DOT (Oklahoma DOT Materials & Research Division 2004) states that one of the most practical tools to clean a weld joint is a stiff wire brush. AWS welding codes allow mill scale that can withstand vigorous wire brushing to remain. According to the welding code, all finished welds must be cleaned as well and recommends that multiple pass welds be cleaned between every pass (Oklahoma DOT Materials & Research Division 2004). Typically, this is accomplished using a chipping hammer and stiff wire brush. A grinder may also be used with care for cleaning, but be used to avoid doing more harm than good on the finished weld and base metal. Risks associated with grinding include excessive removal of base metal and blemishing over weld defects. Slag, which is a byproduct of some welding processes and protects the weld when it is molten, must be removed between passes and at completion of the weld. Failure to clean the surfaces before welding may encourage the formation of porosity in the welds or lack of fusion between the weld and parent material (Miller 1993).

If a project will involve repairing a discontinuity in an existing weld, it is essential that the discontinuity be completely and fully removed prior to the subsequent welding. Grinding the location to bright metal and performing NDT using PT or MT is ideal to ensure complete removal (Miller 1993).

The cleanliness of the materials to be welded is frequently a problem when performing a field repair (Miller 1993). According to the welding codes, loose scale and rust must be removed, at a minimum, before welding. Wire brushing, shot or sandblasting, or grinding are the typical methods used to clean the steel.

AWS D1.1 and D1.5 welding codes require that welding consumables that have been removed from the original package be protected and stored so that the welding properties are not affected. *NCHRP Report 321* reported that it is important that the welding electrodes are dried at high temperatures before use on bridge repair to ensure that the weld metal will have extra low hydrogen content (Gregory et al. 1989). The extra low hydrogen content (of less than 5 ml/100 g) is obtained when low hydrogen electrodes are taken from hermetically sealed containers and dried at 700°F to 800°F for 1 h and used within 2 h after removal.

Heated ovens are required by the AWS welding codes to store low hydrogen electrodes after the hermetically sealed containers are opened in order to maintain their low hydrogen characteristics. Because of the limited electrical power in the field, especially for overnight storage, purchasing electrodes in a small container, such as a 10-lb, hermetically sealed container, may preclude the need for drying ovens if the unused electrodes are thrown away after opening. Coiled electrodes must be protected from direct contact with moisture and condensation.

Weld Fitup

Fitup may be difficult for field welding because of the inability to fixture the pieces or limited access. Field welds are to be designed with consideration of the access and visibility for the welder to perform a quality weld. Welding out of the typical position is likely because the structure cannot be moved to a position of greatest advantage. It is best to select weld joints that will minimize the amount of out-of-position welding (Miller 1993).

Welding Environment

Although the ambient environment where field welding occurs is typically not as controlled as the environment in a bridge fabrication shop, protection from wind and moisture can be provided by constructing a temporary enclosure around the welding location.

Control of the ambient temperature in the immediate area surrounding the point of welding may be required if the temperature is below the limits in the welding code. AWS D1.1 and D1.5 require that the steel be preheated to 70°F if the ambient temperature drops below 32°F. Any additional requirements for preheat beyond this amount will still be required. Welding is not to be performed at an ambient temperature below 0°F in the immediate vicinity around the weld. It is suggested by Miller (1993) that the performance of the welders is negatively affected at such low temperatures and, hence, the practice is discouraged. Protection from low temperatures can be provided by erecting a tent or other protection around the welding location. In this instance, the temperature requirements refer to the temperature within the enclosure at the welding location and not necessarily the temperature outside of the enclosure. It can also be noted that problems with equipment may occur at such low temperatures. For example, the lubricants in the wire feeder gear boxes may thicken at low ambient temperatures, which could adversely affect delivery of the electrode to the arc.

NCHRP Report 321 suggests that electric resistance heating elements with thermocouples and automatic temperature controllers and recorders be used when close control of preheating temperatures is required or when extensive repairs are being performed (Gregory et al. 1989).

Moisture must be controlled during field welding. The base metal must be dry before weld metal is deposited. Preheating the plates before welding can be used to ensure that they are dry; however, an enclosure or cover may be necessary to ensure that they stay dry.

Wind can cause problems with gas arc shielding because it will not allow for adequate coverage of the weld during the welding process. Gas metal arc and gas-shielded flux cored arc welding processes are most sensitive to this issue (Miller 1993). The use of self-shielding flux core or SMAW is often preferred for field welding to avoid problems caused by wind. Where gas-shielded processes are required, a wind screen would be used to protect the gas shielding.

PERFORMANCE OF REPAIRS AND RETROFITS

Little research or published literature was found that specifically documented the performance of field welding, likely because the only inherent difference between field welding and shop welding is where the welding takes place. The welding processes, welding parameters, inspection, and quality requirements are generally the same for field welding as they are for shop welding.

One difference between fabrication shop and field welding is the additional restraint that may be present in a field welded repair or retrofit owing to the structural connections between bridge members. Another difference is that field welding repair and retrofits may be performed while under active live loading, which can cause vibration along with additional dead loading. This concern was mentioned by Zhao and Roddis (2004) and Hu et al. (2006) because micro-cracking could occur within the HAZ as a result of structure vibration during solidification from repairs carried out under traffic. Two research studies were found that attempted to capture these effects by performing experimental testing of fatigue crack weld repair while under tensile stress or dynamic loading.

NCHRP Report 321 described experimental work on repair welded fatigue cracks (Gregory et al. 1989). This research included fatigue testing girders until cracks grew to a predetermined length and then repair welding the cracks before performing additional fatigue testing. The tests demonstrated that repair welds had at least the fatigue life as the original shop weld. Fracture toughness testing was performed that demonstrated that multiple repair welds could be made with minimal toughness reductions in the HAZ. The repair welds met the relevant AASHTO requirements for fracture toughness; however, it was suggested that repairs on FCMs include mechanical testing to qualify the welding procedures and verify that the increased toughness requirements are met.

Experimental work was undertaken to determine the effect of repair welding under dynamic loading when the crack may be opening and closing. It was found that it is possible to carry out repair welding under dynamic loading, but that the preferred procedure was to close the bridge to traffic while the root pass and possibly a second pass of weld metal are deposited. It was determined that welding is an effective and economic method for the repair of fatigue cracks if a good quality weld can be guaranteed. It was stressed that the presence of weld defects can severely reduce the fatigue strength of repair welds.

Another study of the performance of field welded repairs on steel highway bridges was performed in 1984 by Matsumoto and Motomura (1984). This research evaluated the effect of field welding under the influence of load-induced stresses and traffic-induced vibrations that may be present when field welding is done while the bridge is open to traffic. Experimental tests were performed on plate girder bridges to simulate these effects while rewelding fatigue cracks. The tests were done on ASTM A572 Grade 50 and ASTM A678 Grade B steel. This research found that the influence of low tensile stresses on fillet weld defects was almost negligible and that fillet welding can be applied to repair work performed under the influence of tensile stresses. Fillet welding was performed on web plates and flange plates under the influence of vibration. It was concluded that fillet welding can be used to repair web plates and flange plates under the influence of vibration if visual examination and the correction of defects are performed carefully.

Repair procedures for out-of-plane and distortion-induced fatigue cracking utilizing gouging and rewelding of cracks were evaluated by Keating et al. in 1996. This study included field investigation of repairs performed on an in-service bridge, along with laboratory fatigue testing of repairs on large-scale specimens and finite-element analyses. This method was found to be a viable option for the repair of out-of-plane and distortion-induced fatigue cracking as long as proper procedures were followed to achieve a quality repair. The gouging and rewelding technique required a high degree of skill and inspection and, therefore, expense. This type of repair restored the cracked location to its uncracked state; however, without an additional retrofit to lower or eliminate the out-of-plane stresses in this region, the crack would likely reappear. An in-depth inspection including NDT can help ensure complete removal of the crack.

As part of this study, field welding was also performed to connect the existing connection plates to the flange to provide a rigid connection. Concerns with this retrofit included the addition of a fatigue-sensitive detail and the quality of the field welding. Concerns also arose over the inability to adequately clean the joint before welding if the connection plate is tight fit to the flange. Additional grinding may be required to ensure that no paint is in the tight-fit gap.

NCHRP Report 604: Heat-Straightening Repair of Damaged Steel Bridge Girders: Fatigue and Fracture Performance (Connor et al. 2008) investigated the effect of multiple damage repair cycles on the fatigue and fracture performance of steel girders. During this study, many girders required repair welds as a result of cracking induced from impact damage applied in the lab. The impacts were all applied dynamically using a large drop-weight type system. Many of the repairs were significant because of tearing at stiffeners and cover plate details. It was demonstrated that after heat straightening and placement of the repair welds, the repaired welded details did not perform any differently during fatigue testing when compared with the original as-fabricated welds. Although the weld repairs were made in the laboratory, the authors indicated that as long as the repair welds are performed properly and utilize sound welding procedures, there should be no concern as to the performance of the repair welds in terms of fatigue or fracture limit states.

Kelly and Dexter (1997) researched the fatigue performance of repair welds on details commonly implemented on ship structures. Fatigue tests were conducted on full-scale welded beams with a variety of butt welds in the flanges and weld-access holes in the webs. These welds would not meet AASHTO Category B requirements because some of the welds did not have the weld reinforcement ground smooth, backing bars removed, or were welded on one side without backing. The results showed that the fatigue strength of these butt welds corresponded to the AASHTO Category D S-N curve. This fatigue strength was not affected by the type of steel, whether they were two-sided or one-sided welds, whether backing bars were present or removed, and with and without the edges ground flush. Weld-access holes required to make repairs may also be characterized as Category D details. The research included multiple repairs at the same detail by fatigue testing until cracking occurred between each repair cycle. The fatigue testing indicated that the weld repairs of through-thickness cracks have the same fatigue strength as the original new butt welds, even after repairing the same location up to four times.

Fisher et al. (1979) performed GTAW to remelt the weld toes of precracked cover plate termination as reported in *NCHRP Report 206.* It was found that the proper selection of shielding gas and electrode cone angle was necessary to provide adequate penetration to completely remelt the cracks. Mill scale was removed before welding because it was found that undercutting would occur if the scale was not removed. Overhead welding was undertaken to simulate the field conditions for cover plate terminations. It was found that a several hours of training were required before welding personnel could achieve the desired retrofit condition. This research found that GTAW remelting was a successful method for repairing weld toes that have a crack growth less than 0.180 in. deep and 3 in. long, provided that adequate penetration is provided and the operator performs a proper weld. It was also determined that this method could be provided in field conditions under normal traffic loading.

GTAW (also known as TIG) remelting of weld toes to repair fatigue cracks of fillet welds was also investigated by researchers in Japan (Natori et al. 1989). They had findings similar to that of Fisher that the vibration of the bridge under normal service conditions did not affect the GTAW remelt. They recommended the use of GTAW remelting as an effective retrofit technique for cracks less than 2 mm (0.08 in.) deep. Using an assumed crack depth to length ratio of ⅕, it was estimated that cracks of up to 10 mm (0.39 in.) in length can be removed by the GTAW remelting process.

Fisher et al. (1982) recommended the use of field welding to retrofit an out-of-plane cracking detail by welding a shear tab to the transverse connection plate and flange of curved, continuous box girder bridges in Baltimore, Maryland. This retrofit was determined to be the only conceivable possibility in the negative moment region, because cutting back the connection plates to increase the web gap length and provide additional flexibility would likely alter the structural behavior and result in increased adverse behavior. The retrofit was done in 1982, but cracking was observed in the welds during a site inspection in 1984. It was later reported that the cracking was the result of undersized and poor quality welds (Demers and Fisher 1990). In 1986, the shear tabs were partially removed and retrofit holes were drilled in the crack tips. No additional cracks were reported.

Koob et al. (1985) investigated the cracking that occurred on the Poplar Street Bridge in St. Louis, Missouri. It was determined that this cracking occurred because of out-of-plane and distortion-induced fatigue. Various retrofit strategies were investigated, including field welding the connection plates to the top flange of the girder. The main concerns for this repair were the weld quality of overhead welding under the field conditions and the effect of traffic during welding. However, it was determined that a welded retrofit was worthy of evaluation owing to the ease of installation and the good performance record of welded connection plates. Because of concerns about micro-cracking in the HAZ during solidification when welding under live loading, a decision was made to stop traffic during the welding operation for the trial retrofits. Slight undercutting was noted in the top flange weld toe and debris between the stiffener and the top flange caused impurities in the root pass. Poor quality locations were ground out and rewelded. It was determined that sand blasting may not be the most effective method for paint removal because this might have contributed to the trapped debris. A carbide burr grinder was used to weld the toe ground to provide a smooth transition; however, weld toe peening was not done in the trial retrofit. This retrofit was found to eliminate out-of-plane displacement of the web gap; a trial bolted retrofit was also tested in this study and not found to eliminate out-of-plane displacement of the web gap. In the end, a softening technique where the web gap is increased to decrease the stresses was recommended over the field welded retrofit because of concerns over the quality of the field welds.

Kansas DOT performed field welding to repair out-of-plane cracking in the Westgate Bridge, a two-girder bridge consisting of a girder/truss floorbeam/stringer system (Zhao and Roddis 2004). The two girders are 1,758 ft long and are fabricated from A36 material. The bridge was built in 1977, and by 1994 nine of the 11 girder spans had developed horizontal or horseshoe cracks at the interior floorbeam to girder connections. Along with 1-in. stop crack holes being drilled at the end of the cracks, field welding was performed to repair the cracking. In positive moment regions, the web gap locations were stiffened by placing 5⁄16-in. fillet welds to connect the stiffeners to the top flanges. In negative moment regions, ¾ in. stiffener plates were added on the other side of the girders to resist the out-of-plane distortion. Field welds were placed to weld the existing stiffeners to the bottom (compression) flange; however, no welding was placed on the top (tension) flange. The new stiffeners were tight fit to the top flange and cut short where they intersected with existing longitudinal stiffeners. No new crack development has been reported since the bridge was repaired.

Cracking on the Blanchette Bridge over the Missouri River, owned by the Missouri DOT, was noted on stringers after the concrete deck was replaced with a steel grid deck (Marianos et al. 2006). This cracking stemmed from field welds that connected the shim plates of the grid deck to the top flange of the stringers. The stringers conformed to the requirements of ASTM A7 steel, whereas the shim plates were ASTM A36 steel. ASTM A7 steel is generally considered weldable, and no previous indication of welding issues was found during inspection of the fillet welds. An in-depth study was performed by Missouri DOT to determine the cause of cracking. It was determined that the cracking was the result of open shim butt joints where the shim plate was not spliced before being fillet welded to the stringers. This type of cracking would have occurred independent of whether the fillet weld was performed in the field or the shop.

SUMMARY

The literature review revealed that field welded repairs are performed on structures for three primary reasons: fatigue improvement, capacity strengthening, and corrosion and impact damage repairs or retrofits.

- **Fatigue improvement** typically includes retrofit of out-of-plane and distortion-induced cracking by welding the connection stiffener to the flange. In most cases, the welding is on the tension flange. Along with field welded retrofits for out-of-plane cracking, GTAW or TIG welding, to remelts the metal at the weld toe to improve the fatigue resistance.
- **Capacity strengthening** typically involves a retrofit to increase capacity resulting from a poor load rating such as adding stiffeners to increase shear resistance. These repairs are used in cases where the members were designed to support a lighter load than required under current specifications and are distinguished from those where damage of some kind exists.
- **Corrosion and impact damage strengthening** include repair or retrofit of damaged members. Such members may have corrosion damage that has resulted in significant section loss and either requires additional stiffening or complete replacement.

Two primary welding codes are used for structural welding of steel structures in the United States:

- **AWS Bridge Welding Code D1.5** is required for new fabrication of bridges by the AASHTO bridge design specification.
- **AWS Structural Welding Code D1.1** is required for fabrication of buildings and other structures. The specific welding code to be applied to bridge field welding may vary from state to state.

AWS has published a guidance document for the strengthening and repair of existing structures as *AWS D1.7 Guide for Strengthening and Repairing Existing Structures.* Although this document is not a prescriptive code and does not include acceptance criteria, it does contain useful information on things to consider before performing a field welded repair.

Many state DOTs sponsor welder qualification programs where the welder qualification tests are conducted or witnessed by state representatives and a record of field welders who have successfully passed the qualification test can be found in the department's database. These DOTs require that all personnel performing field welding on construction projects pass the welder qualification process and be documented as qualified welders. Many of the state agencies had field welding inspection guides that included information to aid weld inspectors.

The quality of the field welds is a concern that was raised in multiple references. Quality control is more difficult to maintain under field conditions; however, the quality requirements are the same for field welds as shop welds.

Research on field welding has been performed using experimental testing of fatigue crack weld repair while under tensile stress or dynamic loading. These studies found that it is possible to carry out repair welding under dynamic loading; however, the preferred procedure is to close the bridge to traffic while the root pass and possibly a second pass of weld metal are deposited. Other research performed on the fatigue resistance of field welds found that repair welds had at least the fatigue life of the original shop weld, as long as proper procedures were followed to achieve a quality repair. The repair welds met the relevant AASHTO requirements for fracture toughness; however, it was suggested that repairs on FCMs include mechanical testing to qualify the welding procedures and verify that the increased toughness requirements are met. Research has also demonstrated that after heat straightening and placement of the repair welds the repaired welded details did not perform any differently during fatigue testing when compared with the original as-fabricated welds.

Field welded repairs and retrofits that have been implemented on steel bridges and documented in literature have performed well in service. Only one issue with a field welded repair or retrofit was found during the literature review and this was attributed to undersized and poor quality welds.

CHAPTER THREE

STATE OF THE PRACTICE

OVERVIEW

To better understand the current (2015) field welding practices used by state transportation agencies, a survey of practice was conducted through NCHRP in cooperation with AASHTO. Each of the voting members of the AASHTO Subcommittee on Bridges and Structures (SCOBS) was by e-mail for the survey. SCOBS voting members were encouraged to forward the survey to the individual in their agency who would be most familiar with that agency's field welding practices. E-mail reminders were sent to encourage participation. Forty-three state DOTs completed the survey, an 86% response rate.

This chapter summarizes the current practices as derived from the survey. The information is presented in various formats, including both tables and graphs, as appropriate. A copy of the survey questionnaire is included in Appendix B and the agency responses are presented in Appendix C.

SURVEY CONTENT

Survey questions were organized into the following three categories:

- **Policy on Field Welding**—The first question in this section asked participants whether their agency allows planned field welding repairs or retrofits. If not, participants were asked why they chose not to and if they had ever performed planned field welding. If their agency currently does not allow planned field welding and has not ever performed planned field welding, participants were finished with the survey. If their agency either allows planned field welding or has performed planned field welding, participants completed the remainder of the survey. These participants were asked whether their agency has any standard plans, specifications, procedures, or details for certain field welded repairs. If yes, they were asked to provide such information by uploading them electronically or provided a link to any hosted files. Participants were then asked if there was a governing specification or welding code and, if so, what welding code was applied. Finally, participants were requested to describe the types of field welded repair and retrofits that their agency has performed.
- **Field Welding Project Details**—This section of the survey gathered information about the typical design, installation, and quality control and quality assurance requirements for field welding projects. The following design requirements were investigated:
  - Plan and specification preparation, and
  - Base material properties.

  The following installation requirements were reviewed:
  - In-house versus contracted welders,
  - Certified welders, and
  - Welding and inspection procedures.

  The following installation requirements were investigated:
  - Welding inspector requirements, and
  - NDT requirements.
- **Field Weld Performance and Case Examples**—This section of the survey focused on the performance of field welded repairs and retrofits and whether the respondents had experienced field welding that could be shared as either a successful or not successful field welded project case example. The first question in this section asked whether agencies have had any major problems associated with repairs and/or retrofits specifically because they were field welded. If yes, respondents were asked to describe such issues. Respondents were then asked whether they had an experience with field welding on a project, either successful or not, which could be used as a case example. Additional information was then collected on the specific field welded project and whether the respondent was satisfied or not with the field welding on this project.

Survey results are presented in the remainder of this chapter. Representatives from six state DOTs were interviewed to develop case examples of specific field welded projects, which are presented in chapter four.

EXTENT OF FIELD WELDING

Field Welding Policy

Of the 43 state DOTs that responded to the survey, 32 (74%) reported that their agency allows planned field welded repairs and retrofits to be performed. Of the 11 agencies (26%) that do not allow planned field welded repairs/retrofits, two (5%) have previously performed field welding. The remaining nine agencies (21%) have never performed and do not currently allow field welding. Figure 4 shows which agencies allow field

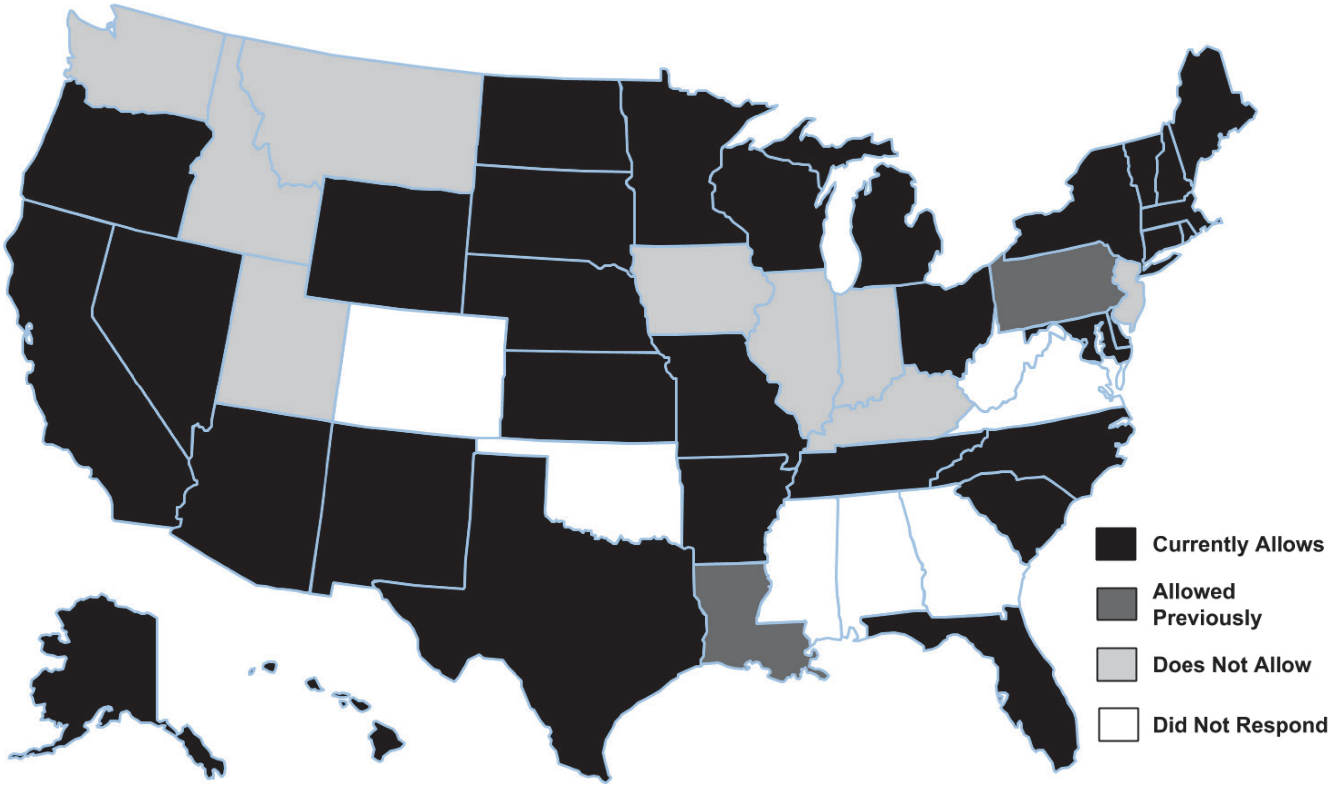


FIGURE 4 Allowance of field welding.

welding currently, allowed field welding previously but do not currently allow it, and which agencies have never allowed field welding.

States as far north as Alaska, North Dakota, Minnesota, and Maine allow field welding; there does not appear to be a correlation with lowest anticipated temperatures and general geographic location and the propensity for field welding.

Figure 5 displays the reasons that 11 state DOTs do not allow field welding that included:

- Lack of experienced inspectors,
- Lack of qualified agency supervisors or administrators,
- Quality of work,
- Unfamiliarity with appropriate welded details,
- Past issues,

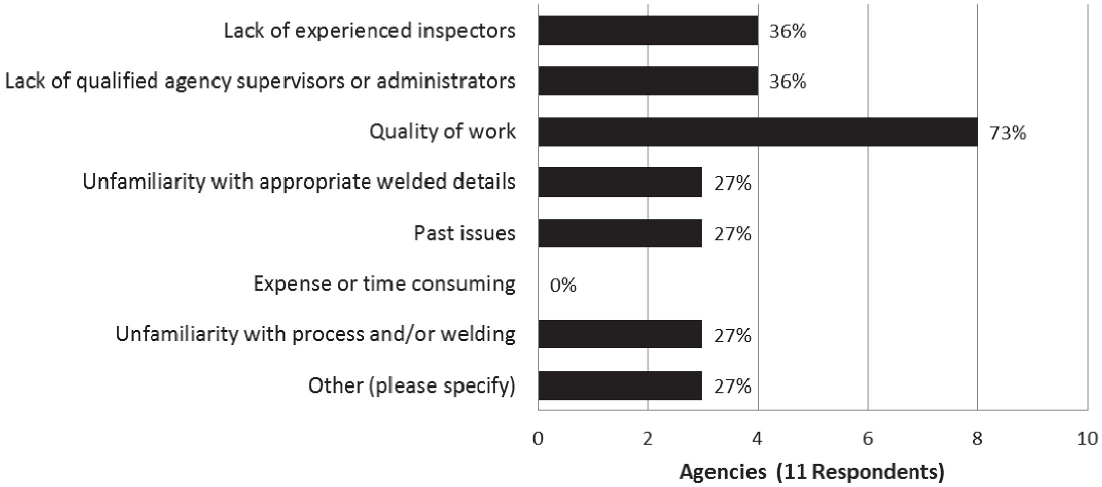


FIGURE 5 Reasons for not allowing field welding.

- Expense or time consuming,
- Unfamiliarity with process and/or welding, and
- Other (please specify).

The most common reason for why agencies do not allow field welding was concerns regarding the quality of work, as indicated by eight of the 11 agencies. The other most often cited responses were a lack of experienced inspectors and a lack of qualified agency supervisors or administrators. Three agencies selected "other" with the following explanations:

- Past performance,
- Welding to a member that is under stress or load, and
- Preferred approach is to provide a structural bolted connection, and the use of field welding is only used as a last resort where there is insufficient room to develop a bolted connection.

The rest of the survey included questions only provided to the 34 agencies that either currently allow field welding or have previously performed planned field welding.

Reasons for Field Welding

Most field welding projects can be grouped into the following three categories.

Fatigue Improvement

This typically includes retrofit of out-of-plane and distortion-induced cracking by welding the connection stiffener to the tension flange. Welding of the transverse stiffeners and connection plates to the tension flange was avoided prior to the early to mid-1980s owing to concerns over fatigue cracking. As a result, a positive rigid connection between the girder flange and web-mounted stiffeners and connection plates was generally not provided. The lack of a positive connection often resulted in cracking from out-of-plane distortions in a plane parallel to the primary loading stress.

Capacity Strengthening

The typically involves a retrofit to increase capacity as the result of a poor load rating such as adding cover plates to a rolled beam bridge. These members are not necessarily damaged and may have been designed to support a lighter load than under current specifications.

Corrosion and Impact Damage Strengthening

This includes repair or retrofit of damaged members. These members may have corrosion damage that has resulted in significant section loss and either requires additional strengthening or complete replacement of the member. Impact damage typically results in distorted and damaged members, including cracking or tearing of the bridge member.

To better understand the most common reasons for field welding, the agencies were asked to select each of the common types of field welding projects they have performed or provide any others that do not fall into these categories. The results are shown in Figure 6. The most common type of field welded project performed was corrosion and impact damage strengthening, with 30 of the 34 possible respondents (88%) reporting that they have performed this type of field welding project. The second most common choice was capacity strengthening.

"Other" was selected by one agency, and it elaborated on this choice by describing the use of field welding to reconnect secondary members and to add plates in compression zones. This would likely fall into both the capacity strengthening and corrosion and impact damage strengthening categories.

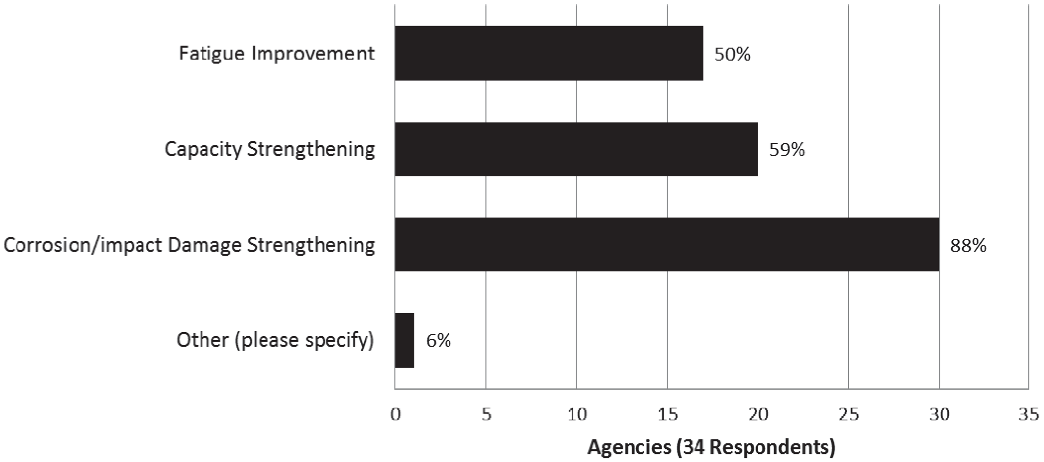


FIGURE 6 Types of field welding projects.

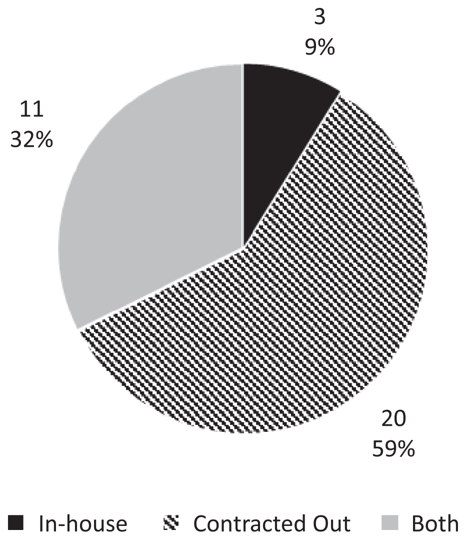


FIGURE 7 Staff performing field welding.

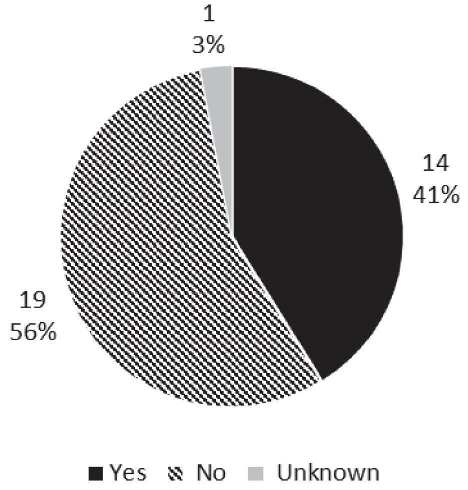


FIGURE 8 Agencies with standard field welding plans, specifications, procedures, or details.

Field Welding Staff

Some agencies may use field welding often enough that they have in-house welders. For other agencies who undertake field welding less often, this may not be economical when compared with hiring an outside contractor to perform these duties. The agencies were asked whether they do field welding with an in-house welding staff, outside contractors, or both depending on the project. Figure 7 shows the answers to this question. It was found that most agencies (20 of 34) contract out their field welding projects. Some agencies use both outside contractors and internal staff, whereas only three use in-house.

CURRENT MANUALS AND SPECIFICATIONS

Standard Plans or Specifications

The 34 agencies that currently perform or previously performed field welding were asked whether they have any standard plans, specifications, procedures, or details for certain field welded repairs. Figure 8 displays the response to this question. A majority of agencies reported that they do not have this type of information for certain field welded repairs.

Although most of the agencies do not have standard field welding plans or specifications, it was determined that the majority always prepare plans or specifications before performing field welding, as shown in Figure 9. No agencies ever require plans or specifications before field welding.

Welding Code Requirements

The 34 agencies that currently perform or previously performed field welding were asked whether they use a governing specification or welding code for field welding projects. Figure 10 displays the responses to this question. Most agencies (27) responded that they "always" require a governing specification or welding code for field welded projects. The second most frequent response was that the use of a governing

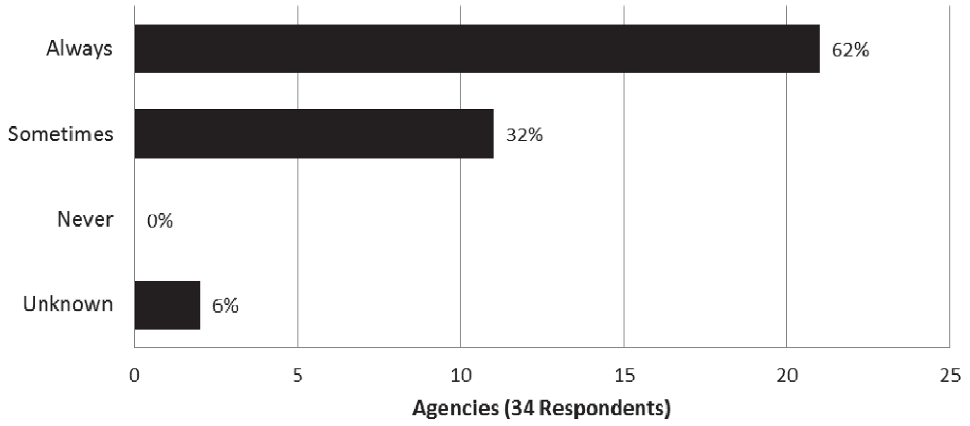


FIGURE 9 Preparation of plans and specifications before welding.

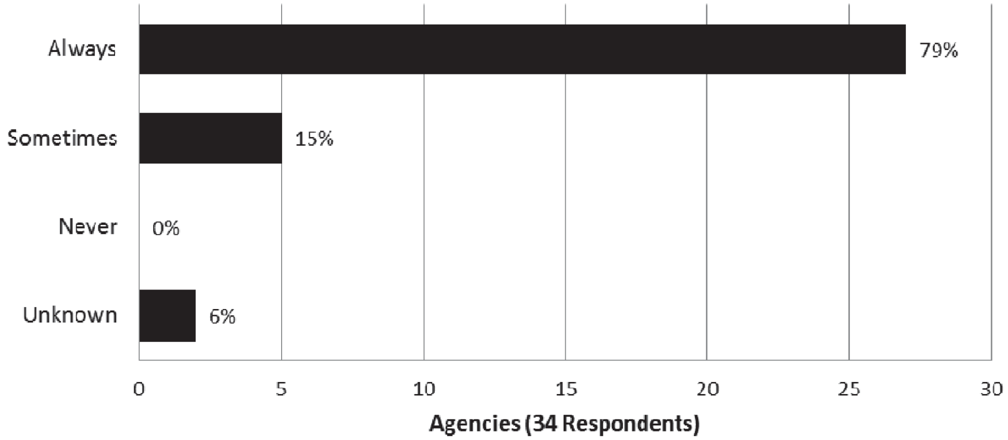


FIGURE 10 Use of governing specification or welding code.

specification or welding code was "sometimes" required. No agencies reported that they never require such a governing specification or welding code.

Although most agencies require the use of a governing specification or welding code, the code most often specified by far is the AASHTO/AWS D1.5 Bridge Welding Code, as shown in Figure 11. Eighty-one percent of the agencies noted that they specify AWS D1.5, whereas only 13% responded that they specify the AWS D1.1 Structural Welding Code, which would be expected because the welding on a bridge component in a fabrication shop would require that this code be followed. Two agencies choose "other" and further explained this choice:

- Combination of D1.5 and internal standard specifications and job special provisions.
- NYS *Steel Construction Manual.*

Base Metal Weldability

Weldability is defined as the capability of a material to be welded under the fabrication conditions imposed and to perform satisfactorily in the intended service. The weldability of steel is often verified before field welding is initiated. Weldability is determined through review of the base material properties.

The agencies were asked about the frequency of projects for which the base material properties were determined before field welding, and the results are shown in Figure 12. An identical number of agencies (14) responded that they either "always" or "sometimes" require base material property determination before field welding. Five agencies responded that it was not known how often base material properties are determined before field welding, and one agency responded that they never require base material determination before field welding.

In a follow-up question, those agencies that responded that they either "always" or "sometimes" require base material properties to be determined before field welding were asked to select each of the following typical methods used:

- Shop drawings,
- Mill test reports,

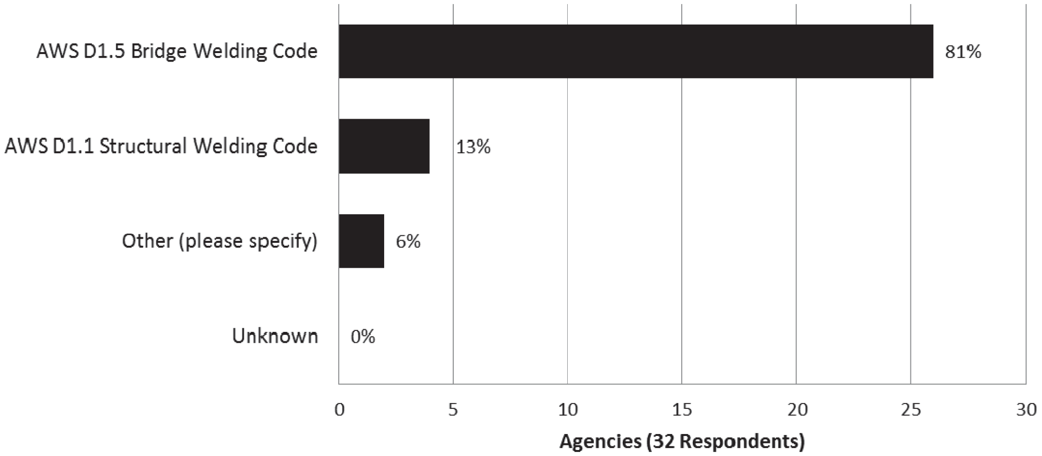


FIGURE 11 Governing welding code.

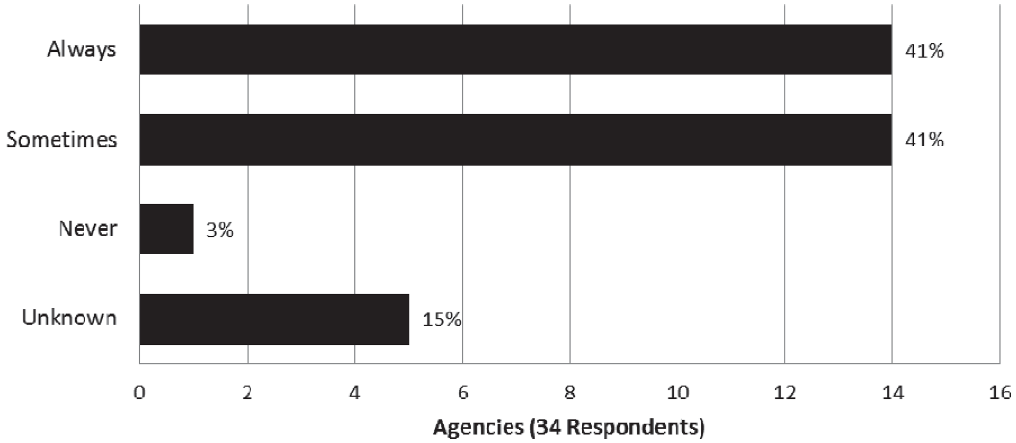


FIGURE 12 Base material properties determination prior to field welding.

- Material samples,
- Using date built information, or
- Other (specify).

This question was presented to 28 agencies and the results are shown in Figure 13. The most common method for determining base material properties was using date built information (20). The use of shop drawings, which generally includes information on the ASTM specification and grade of the steel, and the removal of material samples from the bridge for chemical analysis or coupon testing were the second most common at 17. Utilization of mill test reports, which include the chemical components of the heat of steel used in the manufacturing of the steel plates, was the least frequently cited method at 11. Four agencies also selected "other" and further explained as follows:

- Design drawings,
- As-built drawings,
- Contract plans (mill test reports are not available on many old bridges), or
- Plans.

Unlike material sampling and the information provided in a Mill Test Report, the use of date built information and shop drawings will not provide the actual chemical makeup of the material. However, such methods can be effective in determining the base metal weldability based on historical data or previous experience, but they replace true material sampling to determine base metal properties. When put in the context of the previous question, fewer than half of the agencies always determine base material properties before performing field welding. Two of the most commonly reported methods to determine base material properties do not involve testing of the actual base material.

QUALITY ASSURANCE AND QUALITY CONTROL

Qualification of Welders

A review of welder qualifications is a common requirement in quality assurance and quality control programs. Such requirements are specified in the applicable welding code. It was found that the large majority of agencies used welders certified according to the controlling welding code for the field weld-

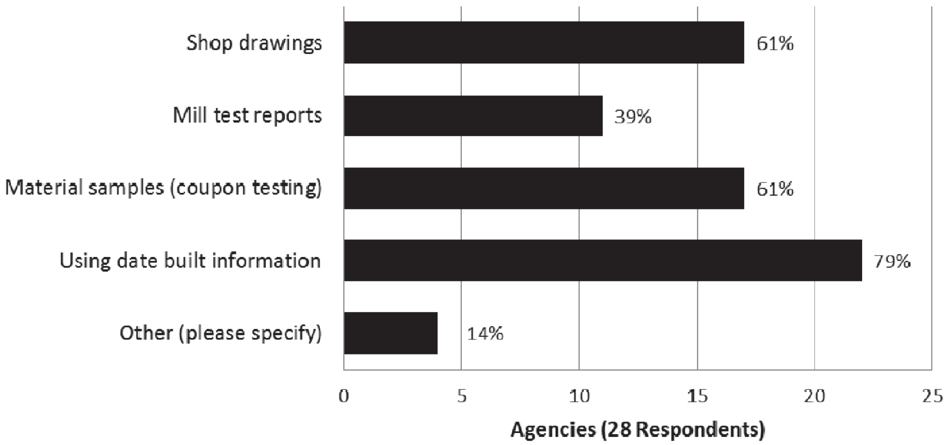


FIGURE 13 Methods to determine base material properties.

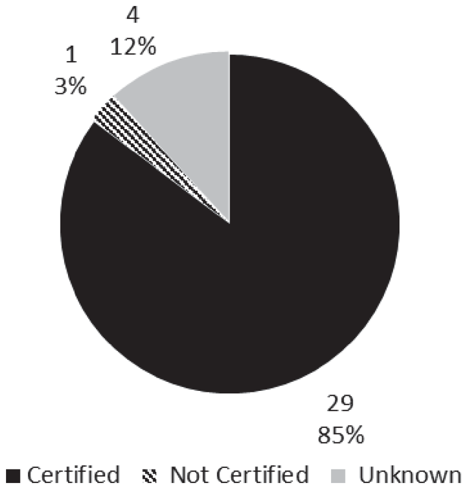


FIGURE 14 Qualification of welders.

ing on their projects, as shown in Figure 14. Four agencies noted that it was not known whether the welders were certified according to the controlling welding code and one stated that it did not use welders who were certified according to this code.

Welding and Inspection Procedures

A detailed welding procedure may be required by an agency before field welding to ensure that the contractor has made the appropriate preparations and accounted for job-specific requirements. Inspection procedures are often included in a quality assurance and quality control program and may be included in a bid package or with project specifications. The agencies were asked about the frequency that they require field welding procedures and/or inspection procedures before performing field welding. As shown in Figure 15, it was determined that the most common response was to "always" require field welding procedures and/or inspection procedures, followed by "sometimes" requiring these procedures. Five agencies responded that they did not know the frequency of projects that had these procedures submitted before welding, and one that it never required field welding procedures and/or inspection procedures before performing field welding.

In a follow-up question, the 28 agencies that responded that they either "always" or "sometimes" require field welding and/or inspection procedures before field welding were requested to select one or more of the following items that are typically included in the field procedures:

- Weld procedures,
- Inspection procedures,
- Welder qualifications,
- Visual inspector qualifications (quality assurance and quality control), and/or
- NDT qualifications (quality assurance and quality control).

Once again, most agencies receive welder qualification as part of a field procedure package (93%) as shown in Figure 16. The second most frequently chosen item was weld procedures, followed by inspection procedures, NDT qualifications, and visual inspector qualifications, all used by at least 50% of respondents.

Inspection Requirements

Agencies were asked whether welding inspectors are required on site. For this question, no distinction was made as to whether these inspections occurred during or upon completion of the welding operation. Figure 17 shows the responses. Twelve agencies (35%) responded that they "sometimes" require on-site welding inspectors and 11 agencies (32%) that they "always" require on-site welding inspectors. Four agencies "never" require on-site welding inspectors for field welding projects.

Typical NDT methods performed on field welds include surface techniques such as dye penetrant testing (PT) and

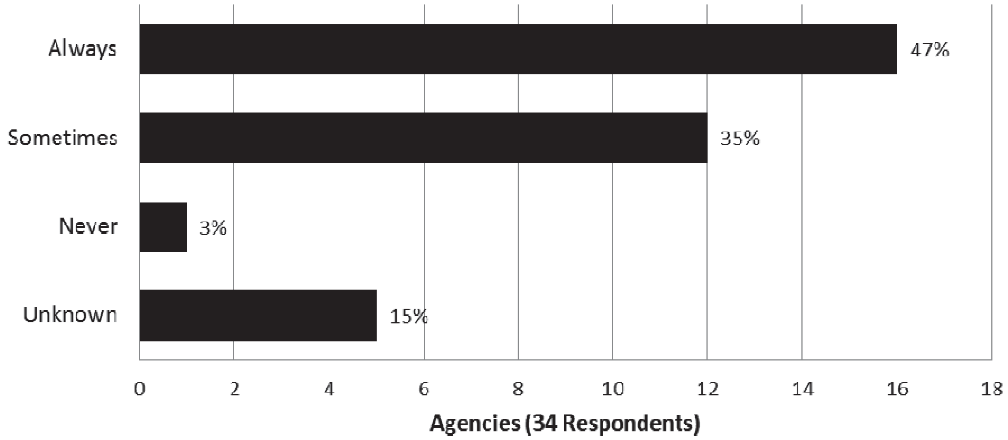


FIGURE 15 Require field welding and/or inspection procedures.

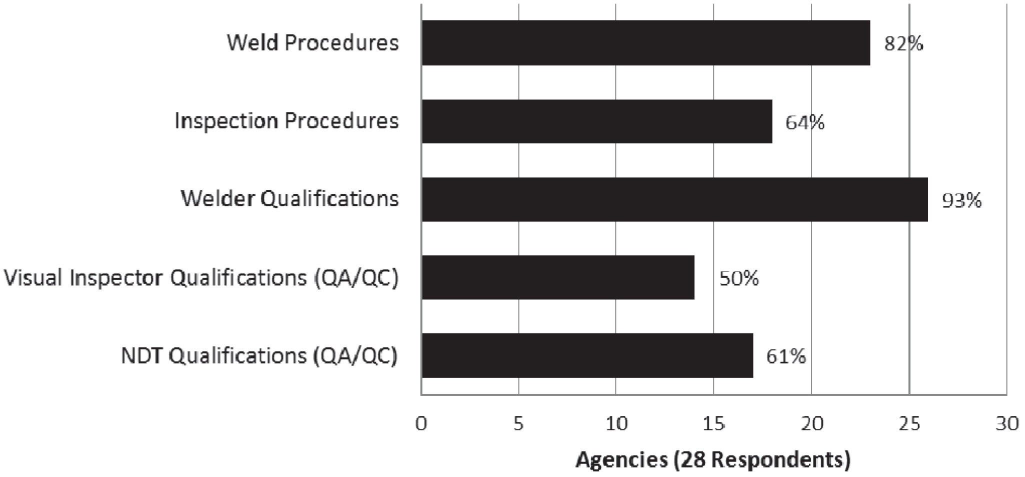


FIGURE 16 Information typically included with field procedures.

magnetic particle testing (MT) and subsurface techniques such as ultrasonic testing (UT) and radiographic testing (RT). Agencies were asked whether NDT is required on field welds. No distinction was made regarding the specific types of NDT methods required. As shown in Figure 18, the most frequent response was that NDT is "sometimes" required on field welds (17), closely followed by NDT is "always" required (14). Only one agency responded that NDT is "never" required on field welds.

PERFORMANCE OF REPAIRS AND RETROFITS

The agencies were asked whether there have been any major problems associated with the repairs and retrofits specifically because they were field welds. This question was asked of all the agencies that answered that they either allow planned field welded repairs and retrofits or have previously performed field welded repairs and retrofits. Results are shown in Figure 19. Seventy percent responded that there have been no major problems associated with repairs and retrofits specifically because they were field welds; six agencies that it was not known whether there have been any major problems because they were field welds, and only four agencies that they have had major problems specifically because they were field welds.

In a follow-up question, the four agencies that had major problems with repairs and retrofits specifically because they were field welds were asked to select one or more of the following items that were at fault:

- Premature cracking,
- Improper welding,
- Quality workmanship (good workmanship practices not followed),
- Not installed in accordance with plans or specifications, and
- Other (please specify).

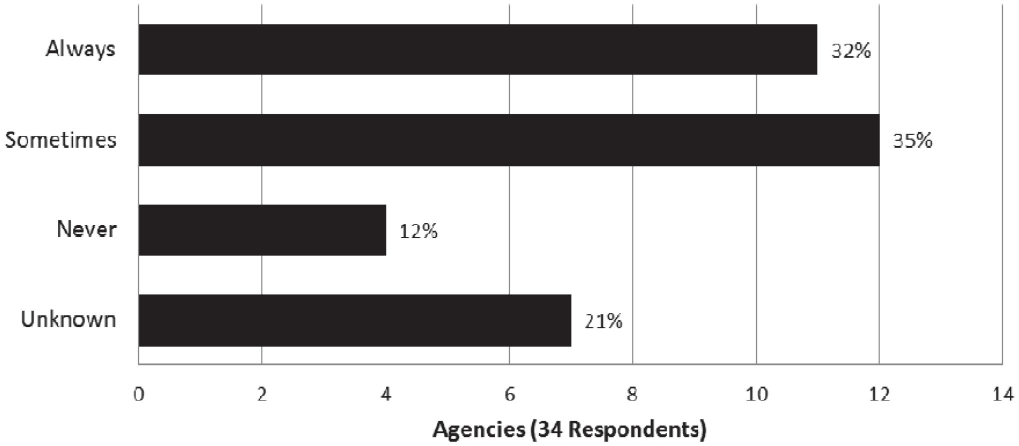


FIGURE 17 Welding inspectors required on site.

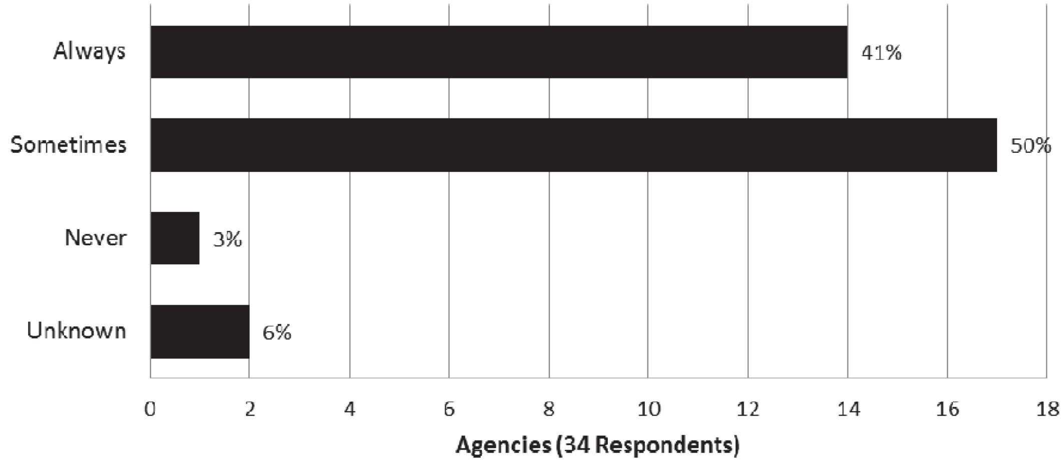


FIGURE 18 NDT required.

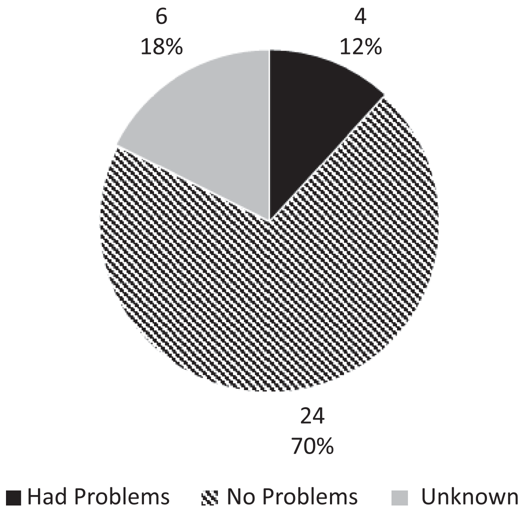


FIGURE 19 Agencies with projects that had major problems as a result of being field welded.

The most commonly reported issue with field welding was premature cracking, which was selected by three of the four agencies, and is shown in Figure 20. Improper welding and quality workmanship issues were the next most common, selected by two of the four agencies. Installation not in accordance with the plans and specifications was selected by one agency.

Further investigation was undertaken on the responses of the four agencies reporting major problems with repairs and retrofits specifically because they were field welds. All four currently allow planned field welding on their bridges. Also, all four use welders certified to internal requirements or the applicable welding code, and all four specify AASHTO/AWS D1.5 Bridge Welding Code for their field welding projects. Three of the four agencies reported that they contract out the welding, whereas one agency reported that it uses both in-house and outside contractor welding staff.

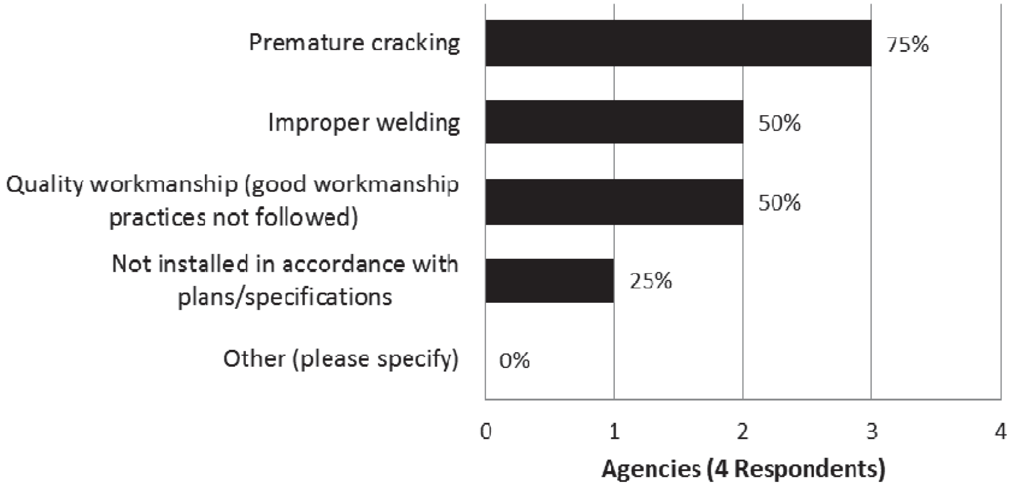


FIGURE 20 Reasons for major issues with field welding.

SUMMARY

Forty-three agencies completed survey responses, an 86% response rate among state DOTs. The primary findings of the survey of the state of practice are summarized as follows:

- Seventy-four percent allow planned field welded repairs and retrofits to be performed.
- Of those agencies that do not currently allow planned field welded repairs and retrofits, only two have previously performed field welding.
- Six agencies provide case examples of field welded projects (see chapter four).
- States as far north as Alaska, North Dakota, Minnesota, and Maine allow field welding:
  - There does not appear to be a correlation with lowest anticipated temperatures and general geographic location and the propensity for field welding.
- Quality of work was the most common reason chosen for why agencies do not allow field welding.
- Most agencies contract out their field welding projects.
- Most agencies require the use of a governing specification or a field welding code:
  - 81% that require a weld code specify AASHTO/AWS D1.5 Bridge Welding Code.
  - 13% that require a weld code specify AWS D1.1 Structural Welding Code, although AASHTO/AWS D1.5 is specifically developed for bridge welding and is specified for bridge fabrication.
- Fewer than half of the agencies reported that they always require base material property determination before field welding:
  - The most common method for determining base material properties involved the use of date built information.
  - The use of shop drawings and removal of material samples were the next most common method to determine base material properties.
  - Use of date built information and shop drawings will not provide the actual chemical makeup of the material.
- It was found that the large majority of agencies used welders certified according to the controlling welding code for the field welding on their projects.
- Less than one-third of the agencies always require welding inspectors, including for inspections that may not be performed until after the welding process has been completed.
- Seventy percent noted that there have been no major problems associated with repairs and retrofits specifically because they were field welds.
- Only four agencies mentioned that they have had major problems with repairs and retrofits specifically because they were field welds.
  - The most common issue with field welding was premature cracking, selected by three of the four agencies.
  - Improper welding and quality workmanship issues were selected by two of the four agencies.

CHAPTER FOUR

CASE EXAMPLES

INTRODUCTION

Individuals from six state agencies were interviewed by phone and e-mail for case examples in order to identify and collect additional information on the field welding practices incorporated into specific projects.

Information collected through the interviews included:

- Bridge type, layout, and location;
- Field welding details;
- Consideration of cost, timing, access, complexity, and alternate repair details;
- Field welding staff;
- Design methodology and preparation of plans and specifications;
- Welding code requirements;
- Inspection requirements;
- Quality control and quality assurance submittals:
  - Welder qualification,
  - Weld procedure,
  - Inspection procedure, and
  - Visual inspector and NDT qualifications;
- Field weld performance; and
- Suggested practices and lessons learned.

The six state transportation agencies selected (Connecticut, Illinois, Maine, Massachusetts, Tennessee, and Texas) were chosen based on several factors including expressed willingness to provide additional information; and details on a field welded project including type of field welded repair, type of bridge, type of bridge member, year bridge was built, and geographic location. This information was captured through the state of practice survey and by direct contact. The survey included additional questions for agencies that had experience with field welding on a project that was or was not successful and expressed a willingness to discuss this experience. Case example participants were then asked to provide the name and location of the project, contact information for someone involved in the project, the reason field welding was used, the estimated number of welds, and whether the field welding was or was not successful. A summary of the information acquired during the state of practice survey and case example interviews is presented in Table 1.

The information presented in this chapter does not provide a comprehensive summary of the field welding practices of these six state agencies; rather, these case examples are intended to focus on a single field welded project performed by each of the six agencies and highlights key field welded practices implemented in these projects.

Four of the six case examples involved repair cracking and other damage resulting from a collision with a bridge girder. One of the field welded case examples concerned repair corrosion damage on the ends of the beams and the sixth case example was a field welded repair of out-of-plane bending.

CASE EXAMPLE 1—CONNECTICUT DEPARTMENT OF TRANSPORTATION

Extent of Field Welding

Bridge Type, Layout, and Location

Bridge No. 00299, which carries I-395 traffic southbound over Route 14 in Plainfield, Connecticut, is a three-span, steel, multi-girder bridge with a cast-in-place deck, with a total bridge length of 123 ft. The bridge was built in 1958 and rehabilitated in 1985.

Field Welding Details

The project involved the removal and repair in June 2014 of a crack in the bottom flange of a non-FCM steel girder resulting from collision damage. Temporary jacking tower and jacking assemblies were installed on either side of the crack. The jacking loads were increased until the crack in the flange was completely closed. Shim plates were then installed on the towers and the jacks unloaded. After the crack was removed, the bottom flange was repaired with a CJP groove weld, which conforms to weld detail B-U2a from the welding code, as shown in Figure 21. The backer bar was removed because of bridge clearance issues. The weld was finished smooth and flush with the base metal on all surfaces by grinding in the longitudinal direction of the girder. After NDT was performed and accepted, the jacks were loaded again to remove the shim plates before releasing the jacking loads, removing the jacking assemblies, and painting the structural steel.

Consideration of Cost, Timing, Access, Complexity, and Alternate Repair Details

There was easy access at the location because the repair was done over a two-lane road; traffic was alternated on the

TABLE 1
CASE EXAMPLES INTERVIEWED

State	Project Name	Location/ Year Built	Bridge Type	Reason for Field Welding	Estimated Number of Welds	Success of Field Welding
Connecticut	Bridge No. 00299	I-395 Southbound over Route 14, Plainfield, CT 1958	3-span, steel, multi-girder with cast-in-place deck	Crack in bottom flange from collision damage	1	very satisfied
Illinois	Structure No. 081-0011	I-80 over Mississippi River near Le Claire, IA 1966	16-span, steel, continuous, two-girder with 12 steel, multi-girder approach spans	Rotation of floorbeam top flange at stringers caused fatigue cracking at web-to-flange fillet weld toe of floorbeam	828	very satisfied
Maine	Hinckley Rd. Repair	I-95 NB over Hinckley Rd. Clinton, ME 1964	3-span, steel, multi-girder, rolled beam composite with cast-in-place deck	Repair work on impact-damaged bridge	6	very satisfied
Massachusetts	Braga Bridge	I-195 over Taunton River Fall River/Somerset, MA early 1960s	3-span, steel, continuous truss with steel, two-girder approach spans	Corrosion—beam end repairs	many	satisfied
Tennessee	Demonbreun St./I-40	Demonbreun St. over I-40 Nashville, TN 1969	2-span, steel, multi-girder, welded plate girder	Collision repair	6	very satisfied
Texas	SH-124 at Intracoastal Waterway	SH-124 over Intracoastal Waterway 50 mi. NE of Houston, TX 1978	Multi-span, steel, three-girder	Vessel impact caused large cracks in plate girders	2	very satisfied

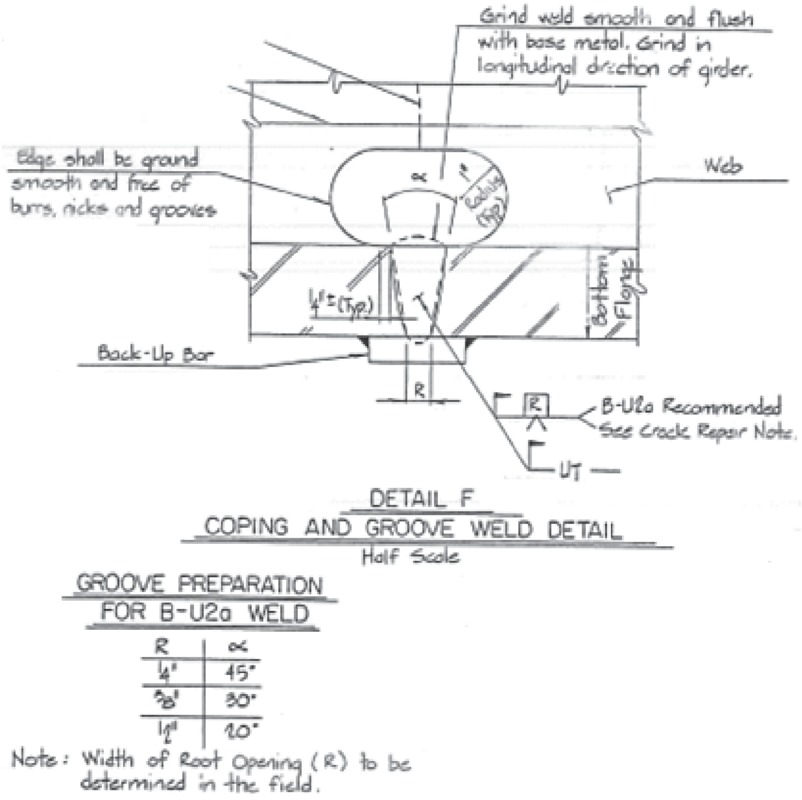


FIGURE 21 Connecticut DOT CJP weld repair sketch.

road below and a shoulder closure on the main road above. The entire repair was completed in one day. The DOT had a contractor under contract for this kind of work; only additional line items on the contract needed to be approved by the contractor.

Field Welding Staff

The DOT intended to perform the field welded repair with state crews because the DOT has several certified field welders on staff; however, it encountered staffing issues. Therefore, an outside contractor, paid on an hourly basis, was hired for the field welding.

Current Manual and Specifications

Design Methodology and Preparation of Plans and Specifications

The agency designed the field welded repair in-house; producing jacking and welding procedures. The weldability of the steel was considered during the design phase and was determined by verifying the type of steel based on the original drawings. This procedure included a sketch of the repair detail, as shown in Figure 21, and notes on the specified welding code, repair procedure, and NDT requirements. The repair procedures were based on those that had been used on a previous project remembered by the bridge design office. It was noted that the welding procedure was controlled by the requirements specified in the AWS D1.1 welding code, the jacking procedure was controlled by the AASHTO LRFD code for jacking loads, and the paint removal and re-application was done according to Connecticut DOT specifications.

Welding Code Requirements

The specified welding code used was AWS D1.1-1980 as modified by the AASHTO Standard Specifications for Welding of Structural Steel Highway Bridges. The welding details, procedures, and testing methods conformed to these requirements. This welding code was specified because it was on the original plan set that was used as a basis for the welding procedure.

Quality Assurance and Quality Control

Inspection Requirements

The DOT provided in-house oversight for the repairs. A qualified inspector was on site each day. The DOT implemented visual inspection, ultrasonic testing of the repair weld, and magnetic particle testing to verify that the crack had been completely removed.

Quality Control and Quality Assurance Submittals

Table 2 contains a summary of the quality control and quality assurance repair and inspection procedures and qualifications.

Performance of Repairs and Retrofits

Performance of the Field Weld

To date, the DOT reports that there have been no issues with the repair and that it was cost-efficient. The crack was in a location of a previous bridge hit, a tension location that has not propagated.

Effective Practices

Connecticut DOT does a significant amount of field welding and endorses it as a satisfactory repair method. The DOT list of the most effective practices for field welding are:

- Take the proper precautions and think about what needs to be done to support the repair welding, relieve the dead load and alleviate the live load if possible,
- Build temporary legs to support the girder on either side of the damaged area, and
- Move traffic from the lane over the affected girder.

Lessons Learned

The agency reported it would not vary the procedure from what they are currently doing. The design engineer noted that he would have liked to have revised the welding code to the latest version.

TABLE 2
CONNECTICUT DOT QUALITY CONTROL AND QUALITY ASSURANCE SUBMITTALS

Submittals	Y/N	Comments
Field Procedures	Y	Written in-house and submitted to the contractor for review and agreement
Welder Qualification	Y	Verified qualifications in-house
Weld Procedure	Y	Formal WPS was not provided by the contractor, but the contractor used the owner submitted step-by-step procedures.
Inspection Procedure	Y	Performed in-house by the DOT
Visual Inspector Qualifications	Y	In-house visual
NDT Qualifications	Y	In-house NDT

CASE EXAMPLE 2—ILLINOIS DEPARTMENT OF TRANSPORTATION

Extent of Field Welding

Bridge Type, Layout, and Location

I-80 over the Mississippi River near La Claire, Iowa, is a 16-span, continuous steel, two-girder bridge, with 12 steel, multi-girder approach spans and a cast-in-place reinforced concrete deck. Total bridge length is 3,483 ft. The structure was built in 1966 and the current rehabilitation occurred in 2010.

Field Welding Details

The two girder spans consist of girders, floorbeams, and stringers with a reinforced concrete deck. The bridge has cantilever floorbeam brackets on the exterior side of the main girders. An inspection performed in May 2009 discovered two top flanges cracked on the floorbeam brackets and one cracked floorbeam bracket web adjacent to the top flange. This damage required immediate action to stabilize the affected areas. Illinois DOT concluded that it was necessary to understand the cause of the cracking before developing a rehabilitation strategy. A consultant was hired to provide an analysis and detailed rehabilitation plans.

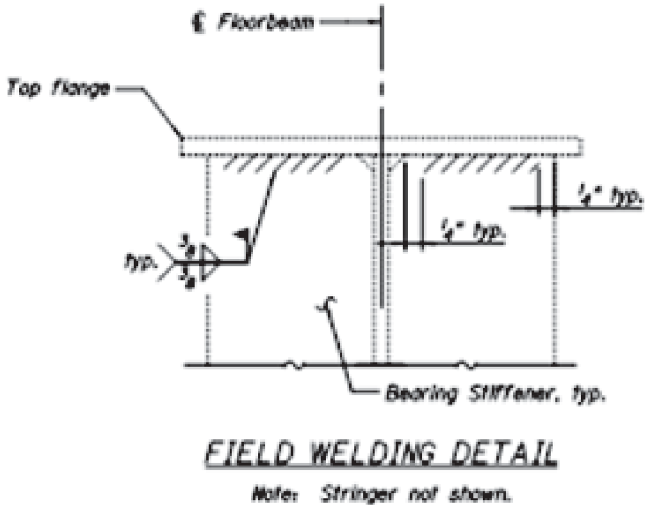


FIGURE 23 Illinois DOT field weld details.

Following an extensive engineering analysis, the cracking was determined to be a result of rocking (out-of-plane bending) at the floorbeam stiffeners caused by live load on the stringers (Figure 22 shows the locations). The stiffeners were originally installed as a tight fit to the top flange (tension flange). At the time this bridge was constructed, welding stiffeners to the tension flange was not a common practice. The stiffeners had a small gap between the stiffener and top flange allowing the flange to rotate, which induced fatigue cracks in the toe of the web-to-flange weld. To repair this, it was necessary to field weld the stiffeners to the top flange and grind out cracks in the weld toe of the web-to-flange fillet weld. A maximum depth of ¼ in. was allowed for grinding, and any locations not meeting this criteria required additional engineering analysis.

Field welding consisted of fillet welding the stiffeners to the floorbeam top flange as shown in Figure 23. After fillet welds were completed, mechanical treatment (ultrasonic impact treatment) was performed on the toe of the fillet welds where the welds intersect the top flange to relieve tensile residual stress and apply a compressive residual stress on the surface to improve the fatigue life of the welds.

Consideration of Cost, Timing, Access, Complexity, and Alternate Repair Details

The DOT considered alternate repair details; however, given the extremely small movements that appeared to be the cause of the cracking, welding provided the most assurance in stop-

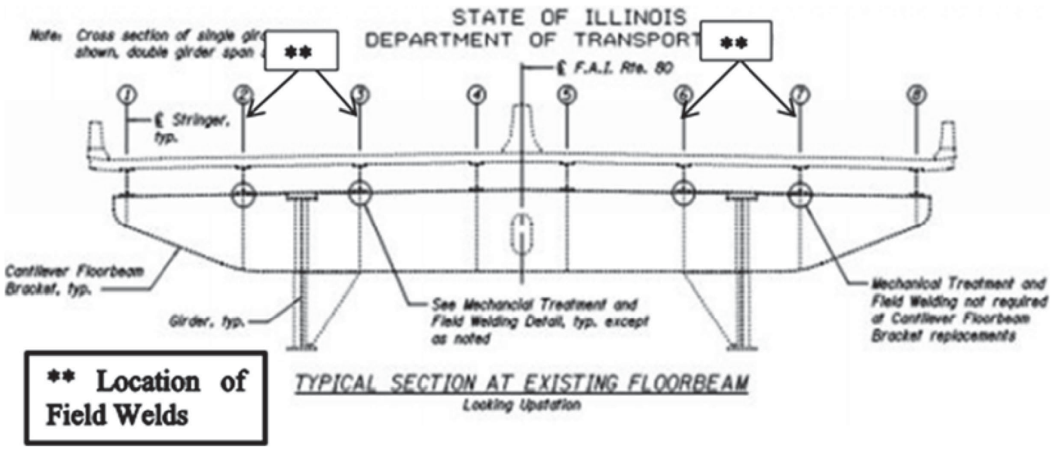


FIGURE 22 Illinois DOT locations of field welding for out-of-plane cracking.

ping the out-of-plane top flange movement. A bolted retrofit may have been possible at some but not all locations as a result of congestion of other surrounding details. Slip critical bolted details might have worked; however, welding provided better assurance of stopping the very small movements. The repair was reported to be cost-effective, including both the welding and UIT. There were unique pay items for both; therefore, the as-bid prices could be provided. For access, temporary working platforms were suspended below the superstructure.

Field Welding Staff

Welders were required to be qualified for overhead position in accordance with AWS Bridge Welding Code D1.5:2008. In addition, the contractor field welding staff was required to perform a one-time, on-site, overhead fillet weld qualification test. The test plate was the fillet weld T-plate in accordance with AWS D1.5:2008 Clause 5.23.1.4. Visual inspection and fillet weld break tests were required. Qualification testing was performed by the contractor's quality control CWI.

Current Manual and Specification

Detailed design drawings were developed from the engineering analysis. Specifications for work were noted on the design drawing for field welding along with special provisions. Work was performed under stringent and detailed requirements. The contractor was required to submit WPSs, CWI qualifications, and NDT qualifications for approval before beginning work. It was necessary that all welders be tested to additional requirements and approved before starting work. Work in the field required extensive cleaning prior to welding, including the removal of paint at least 3 in. beyond the weld zone; no surface rust was allowed and the blast surface needed to meet the requirements of SSPC-10. Continual monitoring by a qualified CWI was required for welding preheat, electrode control, and the welders. Contractor quality control CWI was required to perform visual inspection and NDT.

Design Methodology and Preparation of Plans and Specifications

Extensive engineering analysis was undertaken to determine the cause of the cracking on the top flange of the floor beams at the stringers. This involved evaluating locations where the stringers were continuous over the floor beams and locations where the stringers terminated at a floorbeam. This analysis included extensive field testing that involved strain gages, displacement sensors, tilt meters, and test trucks. From the field testing data, a three-dimensional global model was developed. In addition, a three-dimensional local model was created utilizing a single floorbeam and selected stringers.

Rehabilitation design drawings were developed for the bridge that included partial removal and replacement of the deck and floorbeam brackets at the joints. For the floorbeam brackets that were not removed, a detailed design was developed to perform field welding of the floorbeam stiffeners to the floorbeam top flange, which included material testing to determine the steel weldability.

Welding Code Requirements

All field welding was done in accordance with AWS Bridge Welding Code D1.5:2008, with additional requirements noted on the design plans. These additional requirements specified that all welding be performed with SMAW and that electrode storage and handling be in accordance with AWS, which required constant monitoring by the contractor quality control CWI.

Quality Assurance and Quality Control

Inspection Requirements

The contractor was required to provide full-time quality control by qualified CWI personnel for the field welding. Full-time visual inspection was required as work was performed. If the contractor worked at multiples locations, multiple CWIs were necessary. Quality assurance was the responsibility of the DOT engineer on site during the rehabilitation.

Quality Control and Quality Assurance Submittals

Table 3 is a summary of the quality control and quality assurance repair and inspection procedures and qualifications.

Performance of Repairs and Retrofits

Performance of Field Welds

The DOT reports that the repair has performed well in service; no issues have been identified by follow-up inspections. The agency would use field welding again in a similar situation.

Effective Practices

The DOT prefers to have all welding requirements clearly identified in the contract plans including, but not limited to, weld preparation, preheat, weld procedure, welder qualification, contractor QC requirements, QC staff qualification, and NDT requirements on all welds.

Lessons Learned

The DOT reported that it is not aware of anything that should be done differently on similar future projects.

TABLE 3
ILLINOIS DOT QUALITY CONTROL AND QUALITY ASSURANCE SUBMITTALS

Submittals	Y/N	Comments
Field Procedures	Y	Detailed procedures and design details provided on the design drawings
Welder Qualification	Y	Required to be qualified to AASHTO/AWS D1.5 with additional on-site fillet weld test required
Weld Procedure	Y	Formal WPS was required to be submitted and approved prior to performing work.
Inspection Procedure	Y	Detailed procedures were specified on the design drawings that required full-time inspection.
Visual Inspector Qualifications	Y	Qualified CWIs were required to be approved prior to performing work for all visual inspections per Clause 6 of the Bridge Welding Code.
NDT Qualifications	Y	Qualified personnel were required to be approved before performing work in accordance with Clause 6 of the Bridge Welding Code.

CASE EXAMPLE 3—MAINE DEPARTMENT OF TRANSPORTATION

Extent of Field Welding

Bridge Type, Layout, and Location

Bridge #5995 carries I-95 northbound over Hinckley Road in Clinton, Maine. This bridge is a three-span, steel, multi-girder, rolled beam bridge composite with a cast-in-place deck, consisting of six beam lines. This bridge was built in 1964 and rehabilitated in 1994.

Field Welding Details

This case example involved the repair in fall 2008 of five of the six non-FCM rolled beam girders that were damaged when an aerial lift on a truck struck the bridge. The damage included gouges, cracks, and holes punched through the web by the diaphragms. In three of the beams, the damage required that a portion of the web and bottom flange be replaced by a "T" piece with a partial joint penetration (PJP) weld on the web and a CJP weld on the flanges, as shown in Figure 24. This process involved the use of jacking on the damaged beams during the repair. A ceramic backing bar was used for the CJP weld on the flanges. The web was welded first with a double bevel groove weld before creating the weld-access holes for the flange CJP weld. The flange CJP welds were then performed and, after NDT was performed and accepted, the backup bars were removed and the weld was ground smooth. The new diaphragms were added and the necessary portions of the bridge were repainted.

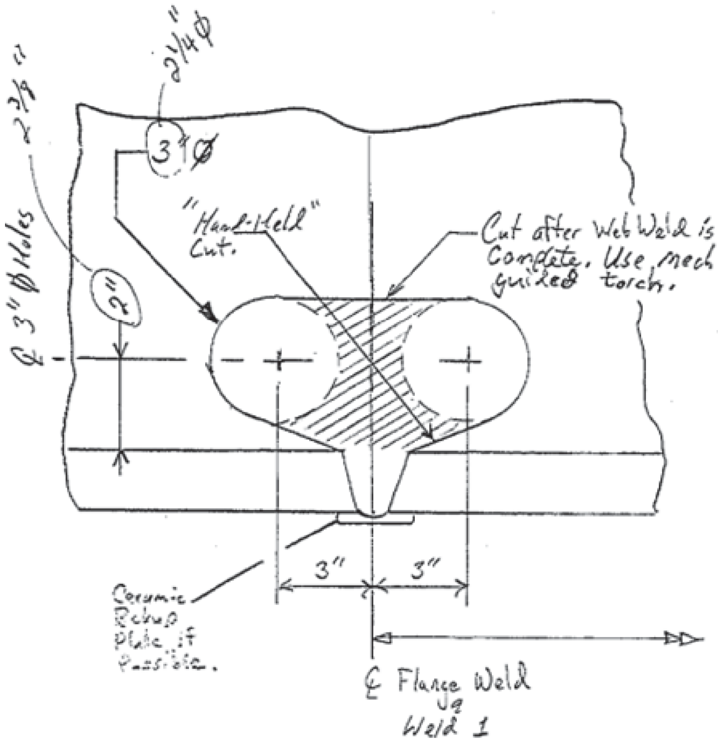


FIGURE 24 Maine DOT CJP weld repair sketch.

Consideration of Cost, Timing, Access, Complexity, and Alternate Repair Details

A bolted splice was considered; however, this type of repair would lower the vertical clearance by 2 in., which would increase the risk of this bridge getting hit again. The DOT likes to control the length of time that a repair is being performed to limit the impact to the public. In total, the repair took four weeks, with total costs controlled by using an in-house crew to fit-up and prepare the weld location. No road closures were required because the only disruption was the jack posts on either side of the repair.

Field Welding Staff

The field welding was contracted out to an experienced outside contractor that had been used previously on similar work. To help control costs, an in-house crew was used to fit-up and prepare the welding locations.

Current Manual and Specifications

Design Methodology and Preparation of Plans and Specifications

The design for the field welded repair was done in-house and produced detailed design sketches and a repair plan, a portion of which is shown in Figure 24. The repair included step-by-step procedures for traffic control, repair implementation, and NDT requirements, along with jacking design plans, paint removal locations, and repair details. Previous field weld repair projects and experience was utilized in the development of the repair procedure and sketches. The weldability of the steel was determined based on the age of the bridge, which was constructed in 1964 and steel from this era tends to have reasonable weldability. WPS was developed for this project.

Welding Code Requirements

A mixture of AASHTO/AWS D1.5 and AWS D1.1 welding codes was used. Most of the requirements came from AWS D1.5; however, it was supplemented with some requirements from AWS D1.1.

Quality Assurance and Quality Control

Inspection Requirements

The agency performed in-house visual inspection of all fit-up before welding for CJP and PJP welds. Magnetic particle testing was done in-house between weld layers on PJP welds and visual inspection was done throughout the repair process with qualified CWIs. Radiographic testing on the CJP welds was performed by a qualified outside contractor.

Quality Control and Quality Assurance Submittals

Table 4 contains a summary of the quality control and quality assurance repair and inspection procedures and qualifications.

Performance of Repairs and Retrofits

Performance of Field Welds

The DOT reports that the repairs are performing well; their intention is to follow-up with a hands-on inspection to ensure that there are no issues. Routine inspections have been performed on the repair every two years and no issues were found. The repair was cost-effective and the agency would do it again. The welding cost was $8,000, steel $5,400, inspection $2,760; and the total cost including heat straightening was $155,000.

Effective Practices

Maine DOT endorses field welding and reports good success with field welded repairs. The most effective practices for field welding are: find the most efficient welder you can and provide the welder with large access holes; employ ceramic backers to aid the welder; use temporary web holders for tight fit-up (take off and place the bolt in hole later); employ a good experienced and enthusiastic crew, and use good equipment (jacking posts and beams).

Lessons Learned

The DOT reported that it is important to ensure that access holes are large enough for the welder.

TABLE 4
MAINE DOT QUALITY CONTROL AND QUALITY ASSURANCE SUBMITTALS

Submittals	Y/N	Comments
Field Procedures	Y	On PJP welds, MT performed on each layer of weld with visual inspection at the completion of the weld. The CJP welds required RT.
Welder Qualification	Y	Require appropriate qualifications
Weld Procedure	Y	Welder and DOT worked together to develop the procedure
Inspection Procedure	Y	In-house procedures
Visual Inspector Qualifications	Y	DOT CWI
NDT Qualifications	Y	Qualified in RT

PJP = partial joint penetration.

CASE EXAMPLE 4—MASSACHUSETTS DEPARTMENT OF TRANSPORTATION

Extent of Field Welding

Bridge Type, Layout, and Location

Charles M. Braga Jr. Memorial Bridge carries I-195 over the Taunton River connecting Fall River, Massachusetts, with Somerset, Massachusetts. The bridge is 5,780 ft long, which includes a three-span continuous truss and two-girder approach spans. The three-span continuous truss, which includes FCMs, has 420-ft end spans with an 840-ft main span, the longest single span in Massachusetts. The two-girder approach spans consist of fracture critical riveted girders. Bridge construction began in 1959 and was completed in 1966. The deck was replaced in the 1980s.

Field Welding Details

This case example involves an ongoing repair of corroded and buckled non-FCM stringer ends caused by leaking deck joints. Approximately 30% of the repairs were performed under a previous contract, which was terminated two and a half years ago, and a new contract put in place to finish the rehabilitation of the bridge. This contract covers fixing the deck joints, which leaked on the stringers and corroded the stringer ends causing some of them to buckle. The repair involves the removal of the buckled end of the beams on the approach and main spans and replacement of the existing stringer end geometry with a WT section that has a CJP weld to the web and flanges, as shown in Figure 25. The stringers ends are cut after jacking with the top flange left in place. There are 16 stringers in the bridge cross section of the bridge, and approximately 130 to 150 stringer end locations require replacement.

Consideration of Cost, Timing, Access, Complexity, and Alternate Repair Details

The DOT has two repair details for the corroded stringer ends. If the web is buckled, the field welded repair is implemented. If the web is not buckled and only corroded, a bolted retrofit using sandwiched plates is performed. The deciding factor in determining whether to field weld was that the webs were already buckled and each new piece was to be custom fitted to match the geometry. It was noted that a bolted connection was never considered for the buckled locations because of the complexity of the geometry.

FIGURE 25 Massachusetts DOT stringer beam end repairs.

Field Welding Staff

The agency contracted out all repairs through a typical bid package.

Current Manual and Specifications

Design Methodology and Preparation of Plans and Specifications

Massachusetts DOT contracted out the design for the field welded repair to a consultant. This design consultant developed a bid package with contract documents for this repair. The contract drawings included repair steps and step-by-step procedures for jacking and shoring. The original base material was matched for replacement material. The DOT standard repair specification was utilized for this project and did not include any specific sections on field welding. The weldability of the steel was verified through material sampling. Base metal samples were taken to run bend, hardness, and chemical testing. Carbon equivalent was also computed to verify weldability. This level of testing was more extensive than the typical material sampling tests that usually only include chemical testing.

Welding Code Requirements

Massachusetts DOT specified AASHTO/AWS D1.5 as the welding code for the field welding.

Quality Assurance and Quality Control

Inspection Requirements

Massachusetts DOT repair welding was done in two phases. For the first phase of the repair, inspections were performed in-house with a qualified CWI. When a new contract was issued to complete the rehabilitation on the bridge, the contractor provided a CWI to perform visual inspection and an outside qualified agency performed 100% UT on the repair welds. The agency also supplied a CWI to spot check the work.

Quality Control and Quality Assurance Submittals

Table 5 contains a summary of the quality control and quality assurance repair and inspection procedures and qualifications.

TABLE 5
MASSACHUSETTS DOT QUALITY CONTROL AND QUALITY ASSURANCE SUBMITTALS

Submittals	Y/N	Comments
Field Procedures	Y	The contract plans show the repair steps including procedures for jacking and shoring.
Welder Qualification	Y	Submitted to the DOT for approval. Mass DOT has an internal welder qualification program that is required for all welders.
Weld Procedure	Y	The contractor developed the weld procedure and it is approved by the DOT.
Inspection Procedure	Y	Listed in the contract documents
Visual Inspector Qualifications	Y	Outside contractor provided qualifications for DOT approval.
NDT Qualifications	Y	Outside contractor provided qualifications for DOT approval.

Performance of Repairs and Retrofits

Performance of Field Weld

The DOT started the repair of stringer ends in 2010 and continued with repairs into 2011. The repairs are performing as expected and no issues have been noted. The repair was cost-effective; considerably less costly than replacing the entire stringer.

Effective Practices

Massachusetts DOT endorses field welding. A considerable amount of field welding is undertaken on a routine basis. The DOT intends to let another project to perform similar stringer end repairs as described in this case example. Its most effective practices for field welding are: use certified welders, have a CWI on-site, outline very clear requirements in the contract, and be as specific as possible.

Lessons Learned

The agency reports that it is very important to have correct details (plans) and specifications for a project. It stressed the need for all projects to have plans and specifications, especially the small projects.

CASE EXAMPLE 5—TENNESSEE DEPARTMENT OF TRANSPORTATION

Extent of Field Welding

Bridge Type, Layout, and Location

This bridge carries Demonbreun Street over I-40 in downtown Nashville, Tennessee, and is a two-span, steel, multi-girder, welded plate girder bridge with span lengths of 102 and 112 ft. The bridge was built in 1969 and consists of 11 beam lines.

Field Welding Details

This case example involved the repair in 2001 of a non-FCM-welded plate girder, which was damaged by impact to the bridge. The damage resulted in two tears in the web at the diaphragms and required that portions of the web be replaced by CJP welds for the web-to-web splice and fillet welds for the web-to-flange welds. The flanges and web were heat straightened; next a 2-ft by 2-ft and a 3-ft by 4-ft section of the web was removed and replaced by welding new sections of the web and stiffeners. This bridge had previously been struck several times and was struck again in 2004 after the 2001 repair. After this hit, the fascia beam that was struck each time because the slope of the roadway below was redesigned with a shallower beam.

Consideration of Cost, Timing, Access, Complexity, and Alternate Repair Details

The DOT did not consider alternate repair details and went straight to field welding because this approach had previously been used on this bridge. During the 2001 repair, the replacement of the girder was evaluated as a result of it being hit repeatedly; however, this was not done at that time owing to the additional cost and because a traffic lane would have to be closed for too long. The beam was later replaced with a shallower beam in 2004 after being hit again. For the 2001 repair, the cost, timing, access, and complexity were considered and it was determined that field welding was the most effective repair method. Field welding can save time because the repairs were completed over two weekends when a lane could be closed.

Field Welding Staff

Tennessee DOT contracted out the welding because flux cored arc welding (FCAW) was performed.

Current Manual and Specifications

Design Methodology and Preparation of Plans and Specifications

The agency designed the field welded repair in-house and created a set of construction plans and drawings. The AASHTO design specification was referenced, along with the specified AASHTO/AWS D1.5 welding code and an internal specification for heat straightening. The weldability of the steel was determined by noting the material specification from the design drawing that showed that it was weldable steel from 1969. Most of the bridge is ASTM A36 steel, with one section of ASTM A441 Grade 50 steel that previously had been welded.

Welding Code Requirements

Tennessee DOT specified AASHTO/AWS D1.5 as the welding code required for field welding.

Quality Assurance and Quality Control

Inspection Requirements

Tennessee DOT provided in-house inspectors who were deemed to be qualified owing to several years of experience, but were not necessarily AWS-certified CWI. Inspection was done on the weld preparation for fit-up. DOT inspectors were on site 100% of the time while weld repairs took place and performed visual inspection on the CJP and fillet welds. Ultrasonic testing was contracted out to a qualified contractor.

Quality Control and Quality Assurance Submittals

Table 6 contains a summary of the quality control and quality assurance repair and inspection procedures and qualifications.

Performance of Repairs and Retrofits

Performance of Field Weld

Tennessee DOT reports that the 2001 repair has been replaced, but that it was in service for 3 years without any problems. This beam had been repaired several times since 1969, and no weld repairs had ever torn following subsequent hits. There were no issues reported for this repair and the agency stated that it was cost-effective.

Effective Practices

Tennessee DOT has performed multiple field repair welds and endorses the continued use of field welding. The agency has found that the most effective practices for field welding are: perform good inspection; require qualified welders with experience in bridge welding, especially if the welders come from a shop; and require written weld procedures.

Lessons Learned

Tennessee DOT noted the importance of ensuring that the contractor is experienced in field work. Some contractors may have been experienced in the shop, but not for field welding. The agency is planning on having a CWI on site at all times in place of in-house inspectors who cannot be there full time. The DOT stressed the importance of full-time observation of the welders.

CASE EXAMPLE 6—TEXAS DEPARTMENT OF TRANSPORTATION

Extent of Field Welding

Bridge Type, Layout, and Location

This bridge, built in 1978, carries SH-124 traffic over the Intracoastal Waterway and is located 20 miles south of Winnie, Texas, or 50 miles northeast of Houston, Texas. The multi-span, steel, three-girder portion of the bridge is 690 ft long with a 290-ft center span. The total length of the bridge including approach spans is 4,300 ft. Because the three-girder portion of the bridge has a 20-foot spacing between girders, these girders are considered to be FCM in accordance with Texas DOT requirements (spacing of 20 ft or more for three-girder bridges).

Field Welding Details

This case example involves December 2013 repair of a FCM girder that was damaged by impact on the bottom flange from a crane on a vessel that struck the bottom flange of the bridge. This bridge is the primary access for residents of the Bolivar Peninsula to mainland Texas. The damage caused cracking in the bottom flange and stiffener, and required that portions of the fillet welds be gouged out and rewelded with new fillet welds.

Consideration of Cost, Timing, Access, Complexity, and Alternate Repair Details

Texas DOT went directly to a field weld repair because the damage was not stress-induced or caused by fatigue. The

TABLE 6
TENNESSEE DOT QUALITY CONTROL AND QUALITY ASSURANCE SUBMITTALS

Submittals	Y/N	Comments
Field Procedures	Y	Contractor submitted a heat straightening plan (general procedures) and weld procedures.
Welder Qualification	Y	AASHTO/AWS D1.5 Bridge Welding Code
Weld Procedure	Y	AWS D1.5
Inspection Procedure	Y	AASHTO/AWS D1.5 for visual and UT
Visual Inspector Qualifications	Y	In-house inspectors internally qualified, not necessarily a CWI
NDT Qualifications	Y	Verified by the DOT

repair was simple because the cracked fillet weld only had to be gouged out and rewelded. This type of repair was cost-effective because it did not require a bid package and was performed in-house.

Field Welding Staff

The DOT performed the field welding in-house; however, they typically will contract out most of their field welding. Over time, less of their field welding has been performed in-house rather than contracted out.

Current Manual and Specifications

Design Methodology and Preparation of Plans and Specifications

The DOT reported that this repair approach was more casual than usual owing to the urgency of the repair because this bridge is the primary access to the Bolivar Peninsula. No specific retrofit details or drawings were developed before the repair was performed, which is unusual for TxDOT. The agency typically designs most repairs in-house and is strict about developing project-specific details and specification; however, the TxDOT standard specification was used on the example project, which includes a section on welding and welding requirements. AASHTO/AWS D1.5 welding code was specified and relied on for additional welding requirements. The weldability of the steel was determined based on the age of the bridge and welding previously performed on the bridge. The steel for this bridge was ASTM A588 weathering steel from 1978.

Welding Code Requirements

TxDOT specified AASHTO/AWS D1.5 as the welding code for field welding and also referenced Item 448 of its internal standard specification, which covers structural field welding.

Quality Assurance and Quality Control

Inspection Requirements

The DOT often replaces a segment of a girder where impact damage has taken place. The CJP welds were 100% radiographic tested by a qualified firm. For the CJP welds and fillet welds, a qualified CWI performed visual inspection.

Quality Control and Quality Assurance Submittals

Table 7 is a summary of the quality control and quality assurance repair and inspection procedures and qualifications.

Performance of Repairs and Retrofits

Performance of Field Weld

TxDOT reports that the repair performed in-service with very good results. The repair was located at mid-span, in the main span, but was not the result of a stress-induced crack. There have been no issues noted in follow-up inspections. The repair was as cost-effective as possible and took only a few hours.

Effective Practices

TxDOT endorses field repair welding, and field welding is used often on its projects. Their most effective practices for field welding include a welder certification program, because every welder employed by TxDOT must be certified through this program. The DOT emphasized enforcing and adhering to the program. It is not sufficient to simply specify a code or specification, the agency requires the presence of an expert CWI on site, full time while work is being performed.

Lessons Learned

The DOT noted that nothing would be different other than monitor gouging out a weld and rewelding more closely.

SUMMARY

The six case examples discussed a variety of the types of field welded repairs that can be performed in the field. Included were repairs for impact damage, corrosion, and out-of-plane bending. Each of the agencies interviewed reported a positive outcome from the field welded repair and plan to continue to utilize field welded repairs on future work. They reported that

TABLE 7
TEXAS DOT QUALITY CONTROL AND QUALITY ASSURANCE SUBMITTALS

Submittals	Y/N	Comments
Field Procedures	Y	No, not in this case. Normally requires contractor to show their intentions in step-by-step procedures, but do not require a formal WPS for field welding.
Welder Qualification	Y	All welders must be certified by the DOT program.
Weld Procedure	N	For this project only—WPSs required on all other projects.
Inspection Procedure	Y	Not on this project, normally require a procedure.
Visual Inspector Qualifications	Y	In-house CWI was used; TxDOT does in-house quality control for field welding with four CWIs on staff.
NDT Qualifications	Y	UT was performed in-house, RT is contracted out.

there were no follow-up problems with the field welded repairs and the repairs were reported to be cost-effective.

- Connecticut DOT does a significant amount of field welding and endorses it as a repair method.
- Illinois DOT stressed the importance of clearly identifying all welding requirements in the contract plans.
- Maine DOT endorses field welding and reports good success with field welded repairs.
- Massachusetts DOT endorses field repair welding and reports that its most effective practices for field welding are the use of certified welders, use of approved welding procedures, having a CWI on site, and having very clear and specific requirements in the contract.
- Tennessee DOT has previously undertaken multiple field repair welds and endorses its continued use. The agency has found that the most effective practices for field welding are efficient inspections, requiring qualified welders with experience in bridge welding, and requiring written weld procedures.
- TxDOT endorses field repair welding, and it is often used on its projects. It reported that the most effective practices for field welding include its welder certification program, because every welder who works for TxDOT must be certified through this program. The agency also emphasized the importance of having an expert CWI on site full time while work is being performed.

Similar points of emphasis were reported by the agencies when asked what was important in achieving a positive outcome to a field welded repair or retrofit. When asked to share some lessons learned, the agencies suggested a variety of items they either corrected, would do differently, or would not change on future projects.

- Illinois, Connecticut, and Texas DOTs stated that they would do nothing different.
- Massachusetts DOT emphasized the importance of correct details and specifications.
- Maine DOT reiterated the importance of good weld access holes for the welder.
- Tennessee DOT stressed the importance of hiring a contractor who was experienced in field welding and the importance of qualified inspectors.

CHAPTER FIVE

CONCLUSIONS

The objective of this synthesis was to document practices and solutions associated with field welded repairs on existing steel bridges that owners have used. The information gathered during this synthesis included the extent to which field welding is performed on existing steel bridges, the common types of field welded repairs and retrofits, and manuals or specifications used for field welded repairs and retrofits. Quality assurance and quality control practices were also investigated, including welder qualifications and testing, material identification, welding procedure development and qualification, and verification inspection. The in-service performance of repairs and retrofits was also reviewed.

Field welding is welding of a material outside of a fabrication shop and typically occurs at a bridge site. Welding on bridge structures in the United States was implemented in the late 1940s and 1950s, but was primarily limited to highway structures. Historically, field welding on highway bridges began to occur on a more frequent basis in the early 1960s into the 1970s. During this time, bridge design and construction transitioned from members comprised of multiple components joined using mechanically fastened members (rivets or bolts) to few elements joined using welds. Welding took place primarily in fabrication shops and sometimes in the field. Field welding differs from shop welding for the following reasons: the welding ambient environment where field welding occurs is not as controlled as the environment in a bridge fabrication shop and the configuration of the steel to be welded cannot be manipulated into position easily. Protection from wind and moisture can be an issue, although protection can be provided by constructing a temporary enclosure around the repair site. Vibrations from live load traffic and dead load residual stress can also be an issue. Field welding for the purposes of repair and retrofit is often performed as repair strategy to mitigate cracks that occurred as a result of these various conditions.

The literature review revealed that field welded repairs are performed on structures for three primary reasons: fatigue improvement, capacity strengthening, and corrosion and impact damage repairs or retrofits.

- **Fatigue improvement** typically includes retrofit of out-of-plane and distortion-induced cracking by welding the connection stiffener to the flange. In most cases, the welding is on the tension flange. Along with field welded retrofits for out-of-plane cracking, gas tungsten arc welding, also known as TIG welding, can be used to remelt the metal at the weld toe to improve the fatigue resistance.
- **Capacity strengthening** typically involves a retrofit to increase capacity resulting from a poor load rating, such as adding stiffeners to increase shear resistance. These repairs are employed in cases where the members were designed to support a lighter load than required under current specifications and are distinguished from those where damage of some kind exists.
- **Corrosion and impact damage strengthening** include repair or retrofit of damaged members. These members may have corrosion damage that has resulted in significant section loss and either require additional stiffening or complete replacement of the member.

The specific welding code to be applied to bridge field welding may vary from state to state. Two primary welding codes are used for structural welding of steel structures in the United States:

- **AWS Bridge Welding Code D1.5** is the welding code required for new fabrication of bridges by the AASHTO bridge design specification.
- **AWS Structural Welding Code D1.1** is the welding code required for fabrication of buildings and other structures.

The American Welding Society (AWS) has published a guidance document for the strengthening and repair of existing structures as AWS D1.7 Guide for Strengthening and Repairing Existing Structures.

Welder qualification programs are instituted by many state departments of transportation (DOTs) where the welder qualification tests are conducted or witnessed by state representatives and a record of field welders who have successfully passed the qualification test are entered into the department's database. These DOTs require that all personnel performing field welding on their construction project pass the welder qualification process and be documented as qualified welders. Many of the state agencies had field welding inspection guides that included information to aid weld inspectors.

The quality of the field welds is a concern that was raised in multiple references. Quality control can be more difficult to maintain under field conditions; however, the quality requirements are the same for both field welds and shop welds. Similar quality control systems and practices are not in place in the field environment as they are in the shop environment.

Research on field welding has been performed that utilized experimental testing of fatigue crack weld repair while under tensile stress or dynamic loading. These studies found that it is possible to carry out repair welding under dynamic loading, but that the preferred procedure was to close the bridge to traffic while the root pass and possibly a second pass of weld metal are deposited. Other research performed on the fatigue resistance of field welds has determined that repair welds had at least the fatigue life as the original shop weld, as long as proper procedures were followed to achieve a quality repair.

Field welded repairs and retrofits that have been implemented on steel bridges and documented in literature have performed well in-service. Only one occasion of problems with a field welded repair or retrofit was found during the literature review and this was attributed to undersized and poor quality welds.

To better understand the current field welding practices used by state transportation agencies, a survey of practice was conducted through NCHRP in cooperation with AASHTO. The survey was distributed to AASHTO Subcommittee on Buildings and Structures (SCOBS) voting members, who were encouraged to forward it to the person within the agency who would be most familiar with that agency's field welding practices.

The main findings of the survey are summarized as follows:

- Seventy-four present of the agencies surveyed allow planned field welded repairs and retrofits to be performed.
- Of the agencies that do not currently allow planned field welded repairs and retrofits, only two have previously performed field welding.
- Although a large number of agencies responded that they allow planned field welded repairs and retrofits, only six provided case examples of field welded projects that met the scope of this project.
- States as far north as Alaska, North Dakota, Minnesota, and Maine allow field welding. There does not appear to be a correlation between lowest anticipated temperatures and general geographic location and the propensity for field welding.
- Quality of work was the most common reason chosen for why agencies do not allow field welding.
- Most agencies contract out their field welding projects.
- Most agencies require the use of a governing specification or welding code:
  - Eighty-one percent that require a weld code specify AASHTO/AWS D1.5 Bridge Welding Code.
  - Thirteen percent that require a weld code specify AWS D1.1 Structural Welding Code even though AASHTO/AWS D1.5 is specifically developed for bridge welding and is specified for bridge fabrication.
- Fewer than half of the agencies responded that they "always" require base material property determination before field welding:
  - The most common method for determining base material properties was by using date built information.
  - The use of shop drawings was the second most common method to determine base material properties with removal of material samples.
  - Use of date built information and shop drawings will not provide the actual chemical makeup of the material.
- A majority of agencies used welders certified according to the controlling welding code for the field welding on their projects.
- Less than one-third of the agencies "always" require welding inspectors, including inspections that may not be done until after the welding process is complete.
- Seventy percent of survey respondents reported that there have been no major problems associated with repairs and retrofits specifically because they were field welds.
- Only four agencies mentioned that they have had major problems with repairs and retrofits specifically because they were field welds:
  - The most common issue was premature cracking, which was selected by three of these four agencies.
  - Improper welding and quality workmanship issues were the next most common, selected by two of the four agencies.

The six case examples discussed a variety of types of field welded repairs. Included were repairs for impact damage, corrosion, and out-of-plane bending. All of the agencies interviewed reported a positive outcome from the field welded repair and plan to continue to implement field welded repairs on future work. There were no follow-up problems reported with the field welded repairs and these repairs were reported to be cost-effective.

- Connecticut DOT does a significant amount of field welding and endorses it as a repair method.
- Illinois DOT emphasized that it is important to clearly identify all welding requirements in the contract plans.
- Maine DOT reported good success with field welded repairs.
- Massachusetts DOT endorses field repair welding and reports the following effective practices: the use of certified welders, the use of approved welding procedures, and having a certified weld inspector on site.
- Tennessee DOT has performed multiple field repair welds and endorses the continued use of field welding. The agency has found that the most effective practices for field welding are: good inspections, requiring qualified welders with experience in bridge welding, and requiring written weld procedures.
- Texas DOT frequently performs field repair welding on existing bridges. The agency has a welder certification program and allows only certified welders to perform

field welding. All welders are to be certified. The agency emphasized the importance of having an expert certified weld inspector on site full time while the work is being done.

Similar points of emphasis were reported by the agencies when asked what was important in achieving a positive outcome to a field welded repair or retrofit. When asked to share some lessons learned, the agencies suggested a variety of items they either corrected, would do differently, or would require on future projects.

- Illinois, Connecticut, and Texas DOTs reported that they would not do anything different.
- Massachusetts DOT stressed the importance of correct details and specifications.
- Maine DOT highlighted the importance of good weld-access holes for the welder.
- Tennessee DOT emphasized the importance of hiring a contractor that was experienced in field welding and the importance of qualified inspection.

The results of the synthesis identified the following gaps in current knowledge that could be addressed by the research activities:

- Identify the effective practices performed by the states that have used field welding correctly.
- Monitor actual field welded repairs and record data on how the fatigue life of the repair may be influenced by environment, vibration, dead load and live load stresses, and quality.

GLOSSARY

Adapted from AWS A3.0 (AWS 2010).

Arc strike—A discontinuity resulting from an arc consisting of any localized remelted metal, heat-affected metal, or change in surface profile of any metal object.

Back gouging—Removal of weld metal and base metal from the weld root side of a welded joint to facilitate complete fusion and complete joint penetration upon subsequent welding from that side.

Backing—A material or device placed against the back side of the joint to support and retain molten metal. A material or device placed against the back or the side of the joint adjacent to the joint root or at both sides of a joint in electroslag and electrogas welding, to support and shield molten weld metal. Material may be partially fused or remain unfused during welding and may be either metal or nonmetal.

Base material (metal)—Material to be welded.

Base metal—Metal or alloy that is welded, brazed, soldered, or cut.

Carbon equivalent (CE)—An empirical value in weight percent, relating the combined effects of different alloying elements used in the making of carbon steels to an equivalent amount of carbon. This value can be calculated using a mathematical equation.

Certified Weld Inspector (CWI)—An AWS-certified weld inspector performs visual inspections on welded steel pieces to be used in the construction of bridges and other structures. They must be able to detect possible welding defects, use test and measuring instruments, and monitor any repairs to faulty welds.

CJP (complete joint penetration) groove weld—A joint root condition in a groove weld in which weld metal extends through the joint thickness. A groove weld that has been made from both sides or from one side on a backing having complete penetration and fusion of weld and base metal throughout the depth of the joint.

Crack—A fracture type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement.

Engineer—A duly designated individual who acts for and/or in behalf of the owner on all matters within the scope of the work.

Fatigue—Weakening or breakdown of a material as a result of repeated cycles of stress.

Field welding—Welding that occurs outside of a fabrication shop. Welds made at a location other than the shop or the place of initial construction.

Fracture critical member—Steel tension members or steel tension components of members whose failure would be expected to result in the partial or full collapse of the bridge.

Heat affected zone (HAZ)—Portion of the base metal where the mechanical properties or microstructure have been altered by the heat of welding, brazing, soldering, or thermal cutting.

Inspection—Examination by the Owner or the Fabricator of processes and products to verify conformance with contract requirements.

Mill Test Report (MTR)—A quality assurance document used to certify a material's chemical and physical properties and that states the material's compliance with an international standards organization specific standard.

Nondestructive examination (NDE)—The act of determining the suitability of some material or component for its intended purpose using techniques that do not affect its serviceability.

Nondestructive testing (NDT)—Analysis techniques used to establish the properties of a material or identify defects in a material or member without causing damage to the material or member.

Partial joint penetration (PJP)—A joint root condition in a groove weld where weld metal extends partially through the joint thickness. Joint penetration that is intentionally less than complete. A portion of the joint is not fused.

Porosity—Cavity-type discontinuities formed by gas entrapment during solidification or in a thermal spray deposit.

Preheating—Application of heat to the base metal immediately before welding brazing, soldering, thermal spraying, or cutting. The heat applied to the base metal or substrate to attain and maintain preheat temperature.

Procedure Qualification Record (welding)—A document providing the actual welding variables used to produce an acceptable test weld and the results of tests conducted on the weld to qualify a Weld Procedure Specification.

Quality assurance (QA)—Quality assurance encompasses the activities undertaken by the Owner to verify that the final product satisfies contract requirements, including verifying that quality control is performed effectively.

Quality control (QC)—Activities undertaken by the Contractor or Fabricator to ensure a product is provided that meets contract requirements.

Residual stress—Stress present in a joint member or material that is free of external forces or thermal gradients.

Undercut—A groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal.

Weld Procedure Specification (WPS)—The demonstration that welds made by a specific procedure can meet prescribed standards. A document providing the required welding variables for a specific application to ensure repeatability by properly trained welders and welding operators.

Weldability—Capacity of a material to be welded under the fabrication conditions imposed into a specific, suitably designed structure and to perform satisfactorily in the intended service.

Welder—One who performs a manual or semiautomatic welding operation.

Welder certification—Written certification that a welder has produced welds meeting a prescribed standard of welder performance.

Welder performance qualification—The demonstration of a welder's ability to produce welds meeting prescribed specified standards.

Welding—A joining process that produces coalescence of materials by heating them to the welding temperature, with or without the application of pressure or by the application of pressure alone, and with or without the use of filler metal.

Welding electrode—A component of the welding circuit through which current is conducted and that terminates at the arc, molten conductive slag, or base metal.

Welding symbol—A graphical representation of the specifications for producing a welded joint.

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APPENDIX A

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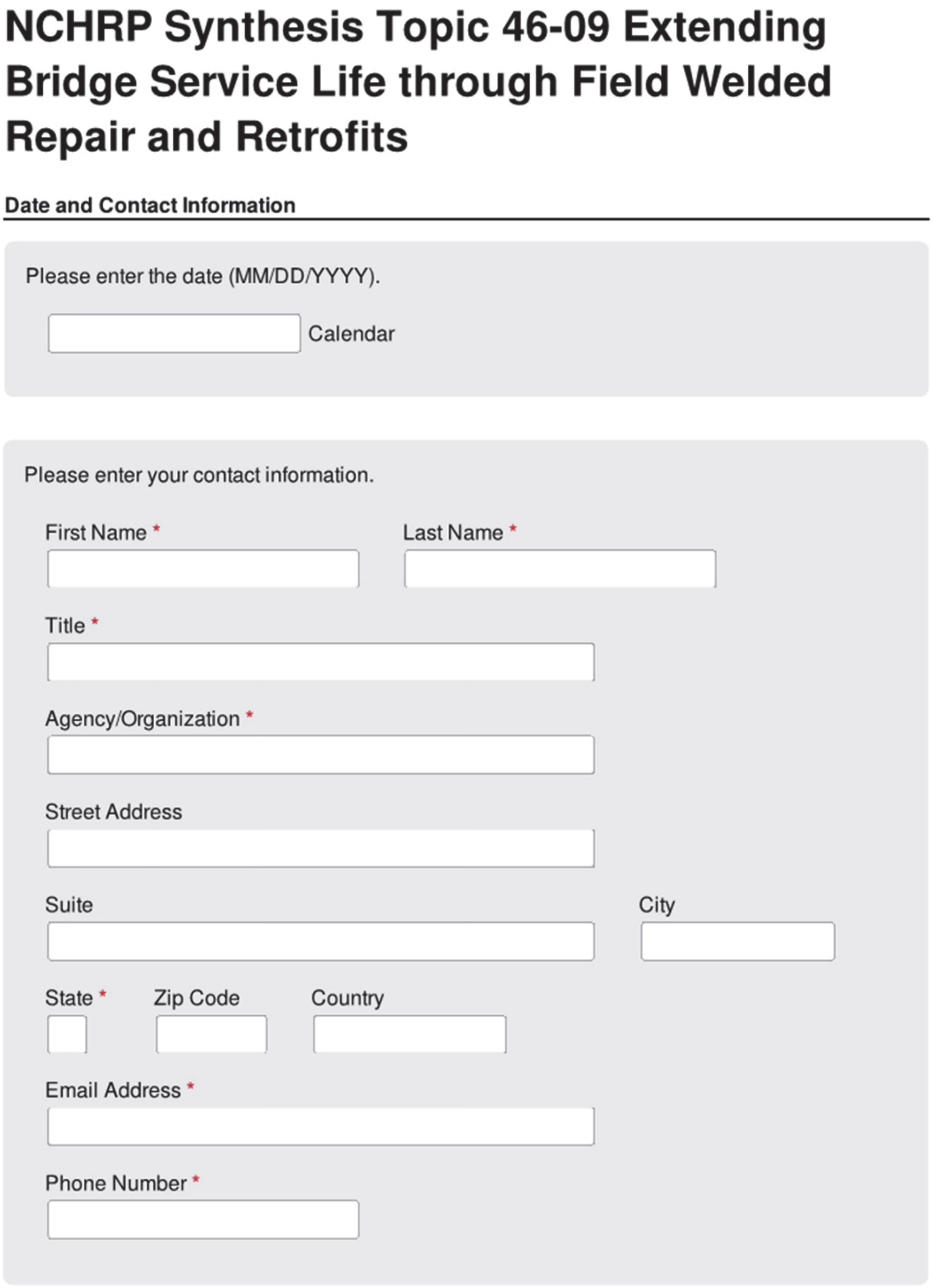
APPENDIX B

Survey Questionnaire



NCHRP Synthesis Topic 46-09 Extending Bridge Service Life through Field Welded Repair and Retrofits

Date and Contact Information

Please enter the date (MM/DD/YYYY).

Calendar

Please enter your contact information.

First Name *

Last Name *

Title *

Agency/Organization *

Street Address

Suite

City

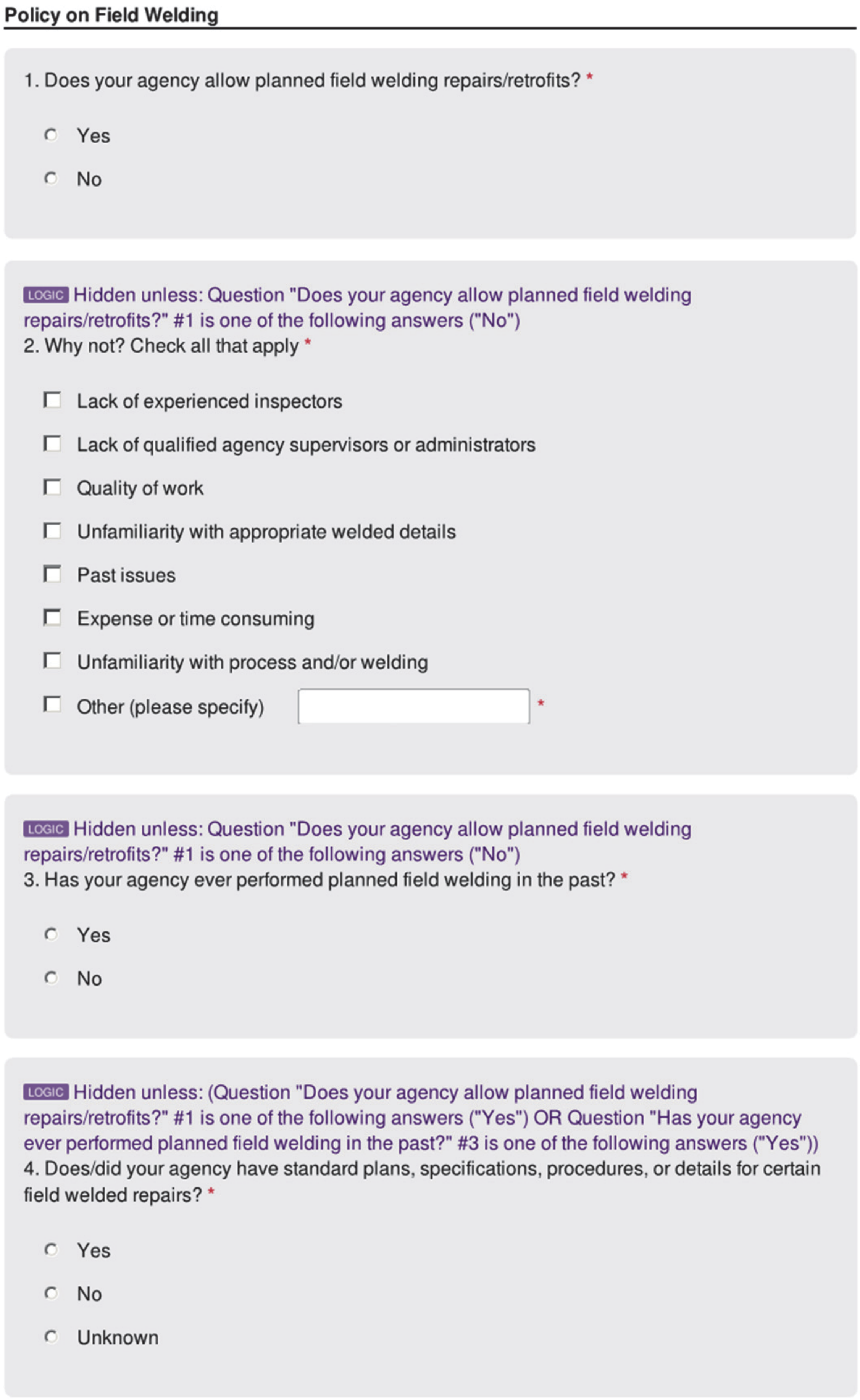
State *

Zip Code

Country

Email Address *

Phone Number *



Policy on Field Welding

1. Does your agency allow planned field welding repairs/retrofits? *

○ Yes

○ No

LOGIC Hidden unless: Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("No")

2. Why not? Check all that apply *

☐ Lack of experienced inspectors

☐ Lack of qualified agency supervisors or administrators

☐ Quality of work

☐ Unfamiliarity with appropriate welded details

☐ Past issues

☐ Expense or time consuming

☐ Unfamiliarity with process and/or welding

☐ Other (please specify) ________ *

LOGIC Hidden unless: Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("No")

3. Has your agency ever performed planned field welding in the past? *

○ Yes

○ No

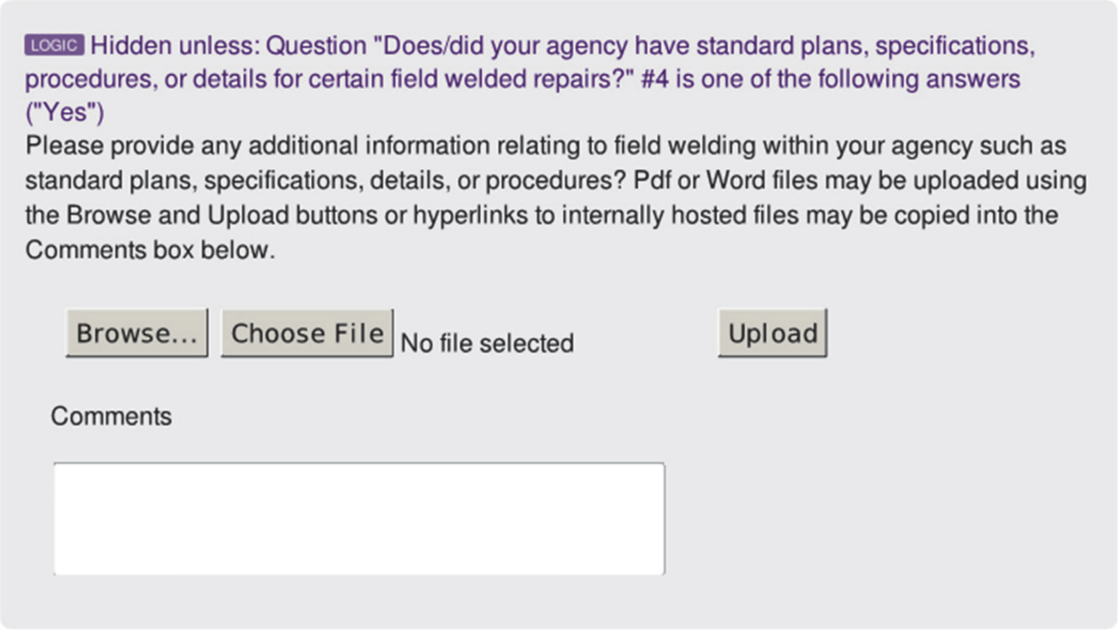
LOGIC Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))

4. Does/did your agency have standard plans, specifications, procedures, or details for certain field welded repairs? *

○ Yes

○ No

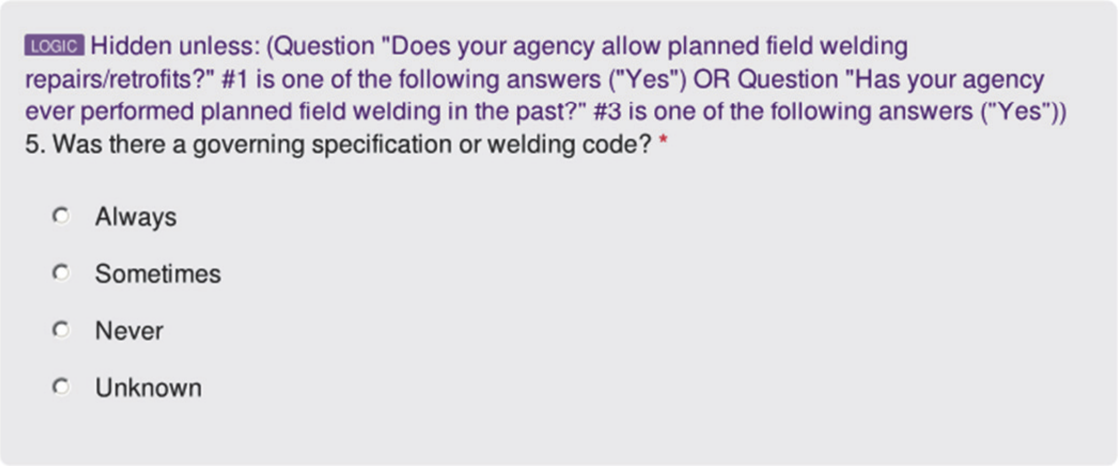
○ Unknown



Hidden unless: Question "Does/did your agency have standard plans, specifications, procedures, or details for certain field welded repairs?" #4 is one of the following answers ("Yes")

Please provide any additional information relating to field welding within your agency such as standard plans, specifications, details, or procedures? Pdf or Word files may be uploaded using the Browse and Upload buttons or hyperlinks to internally hosted files may be copied into the Comments box below.

Comments



Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))

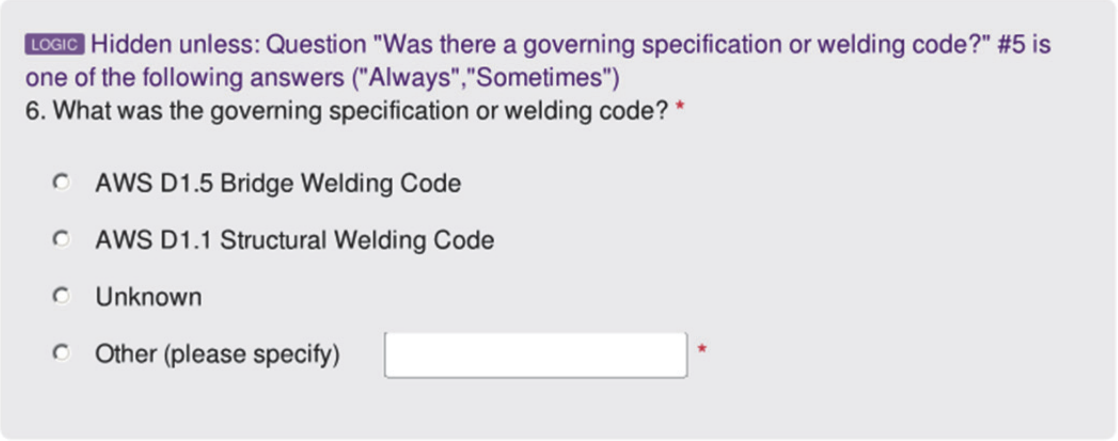
5. Was there a governing specification or welding code? *

○ Always

○ Sometimes

○ Never

○ Unknown



Hidden unless: Question "Was there a governing specification or welding code?" #5 is one of the following answers ("Always","Sometimes")

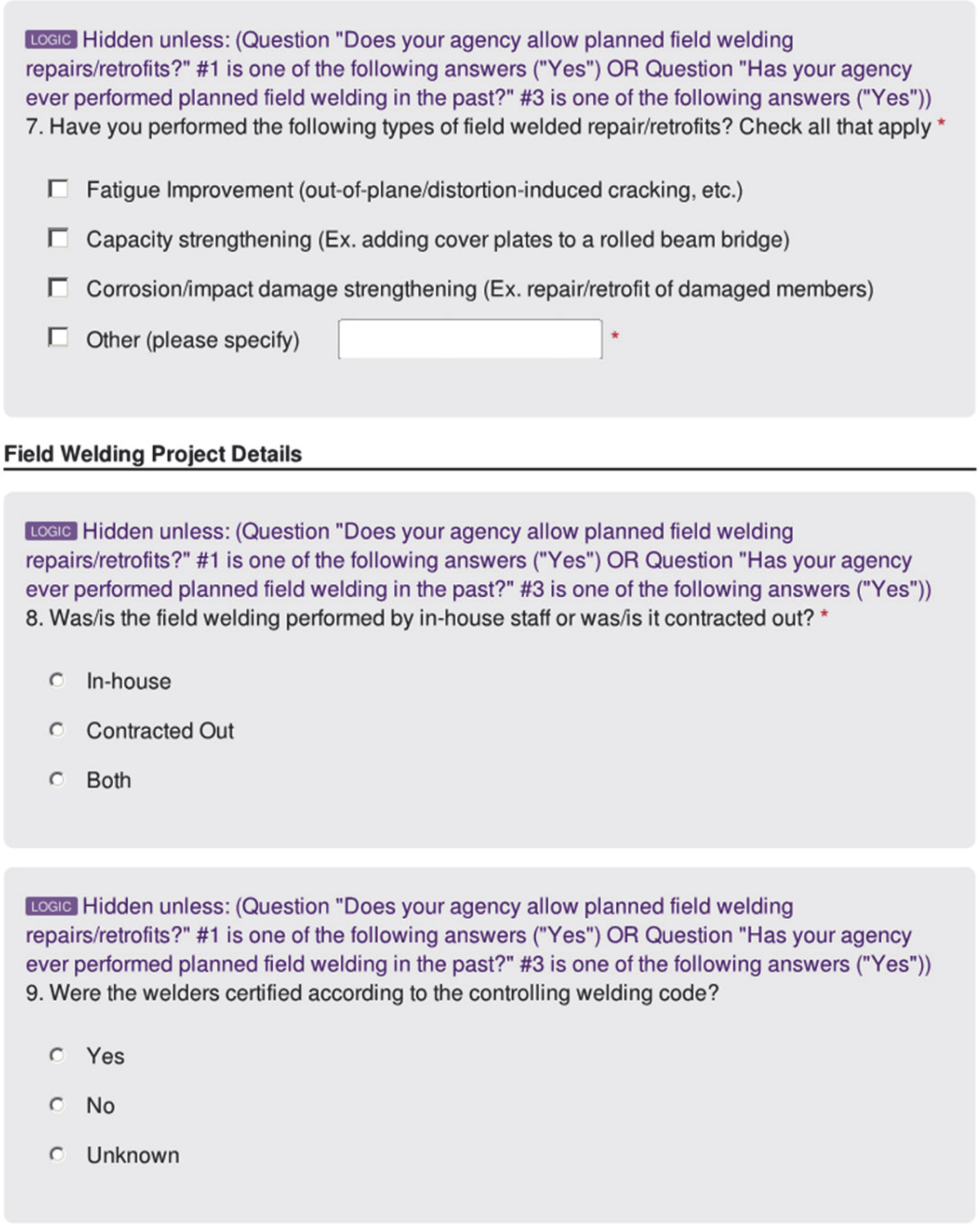
6. What was the governing specification or welding code? *

○ AWS D1.5 Bridge Welding Code

○ AWS D1.1 Structural Welding Code

○ Unknown

○ Other (please specify) *



LOGIC Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))
7. Have you performed the following types of field welded repair/retrofits? Check all that apply *

☐ Fatigue Improvement (out-of-plane/distortion-induced cracking, etc.)

☐ Capacity strengthening (Ex. adding cover plates to a rolled beam bridge)

☐ Corrosion/impact damage strengthening (Ex. repair/retrofit of damaged members)

☐ Other (please specify) ______ *

Field Welding Project Details

LOGIC Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))
8. Was/is the field welding performed by in-house staff or was/is it contracted out? *

○ In-house

○ Contracted Out

○ Both

LOGIC Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))
9. Were the welders certified according to the controlling welding code?

○ Yes

○ No

○ Unknown

LOGIC Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))
10. Were plans/specifications prepared before the work was performed? *

- ○ Always
- ○ Sometimes
- ○ Never
- ○ Unknown

LOGIC Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))
11. Were field welding and/or inspection procedures prepared before work was performed? *

- ○ Always
- ○ Sometimes
- ○ Never
- ○ Unknown

LOGIC Hidden unless: Question "Were field welding and/or inspection procedures prepared before work was performed?" #11 is one of the following answers ("Always","Sometimes")
12. Which of the following items were typically included in the field procedures? Check all that apply

- ☐ Weld Procedures
- ☐ Inspection Procedures
- ☐ Welder Qualifications
- ☐ Visual Inspector Qualifications (QA/QC)
- ☐ NDT Qualifications (QA/QC)

LOGIC Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))

13. Are welding inspectors required on-site to inspect field welds? (During welding operation and/or after completion of welds) *

○ Always

○ Sometimes

○ Never

○ Unknown

LOGIC Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))

14. Is non-destructive testing required on field welds? *

○ Always

○ Sometimes

○ Never

○ Unknown

LOGIC Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))

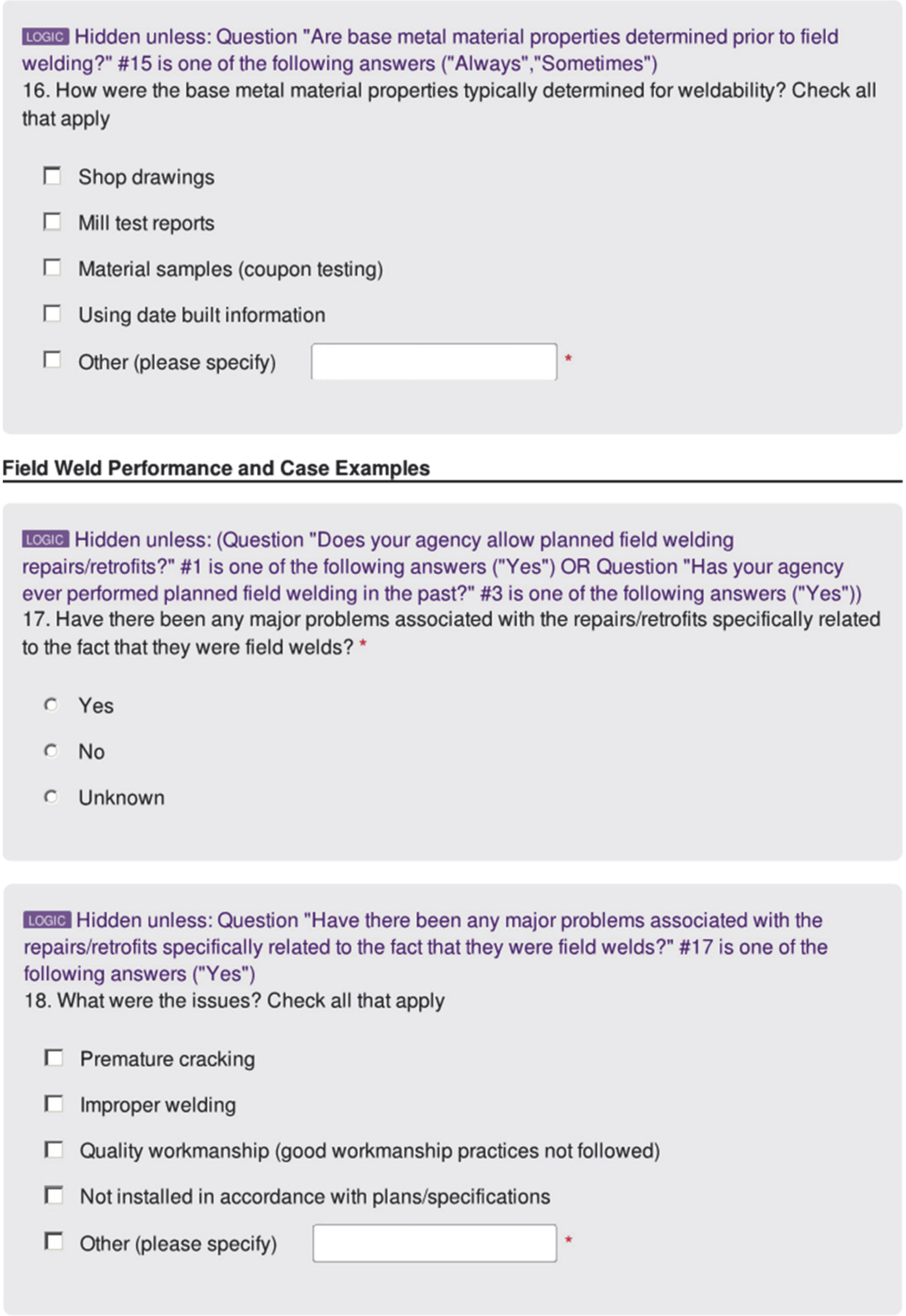
15. Are base metal material properties determined prior to field welding? *

○ Always

○ Sometimes

○ Never

○ Unknown



LOGIC Hidden unless: Question "Are base metal material properties determined prior to field welding?" #15 is one of the following answers ("Always","Sometimes")

16. How were the base metal material properties typically determined for weldability? Check all that apply

☐ Shop drawings

☐ Mill test reports

☐ Material samples (coupon testing)

☐ Using date built information

☐ Other (please specify) __________ *

Field Weld Performance and Case Examples

LOGIC Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))

17. Have there been any major problems associated with the repairs/retrofits specifically related to the fact that they were field welds? *

○ Yes

○ No

○ Unknown

LOGIC Hidden unless: Question "Have there been any major problems associated with the repairs/retrofits specifically related to the fact that they were field welds?" #17 is one of the following answers ("Yes")

18. What were the issues? Check all that apply

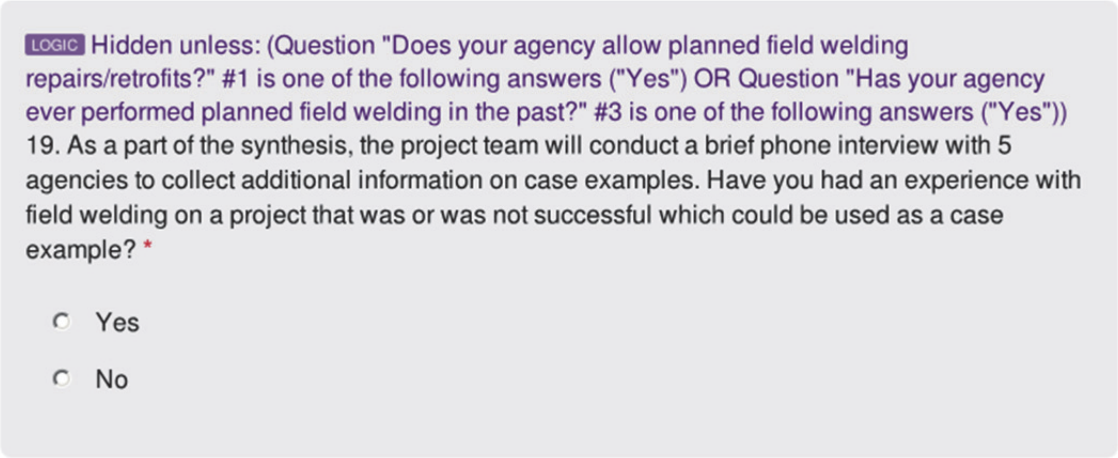
☐ Premature cracking

☐ Improper welding

☐ Quality workmanship (good workmanship practices not followed)

☐ Not installed in accordance with plans/specifications

☐ Other (please specify) __________ *

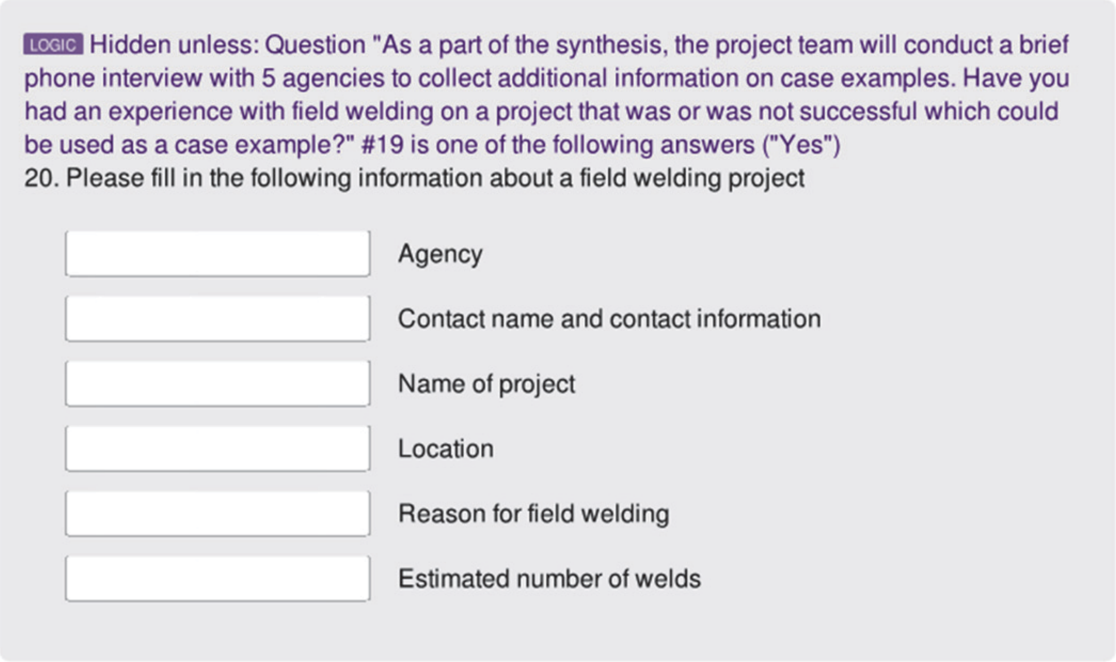


LOGIC Hidden unless: (Question "Does your agency allow planned field welding repairs/retrofits?" #1 is one of the following answers ("Yes") OR Question "Has your agency ever performed planned field welding in the past?" #3 is one of the following answers ("Yes"))

19. As a part of the synthesis, the project team will conduct a brief phone interview with 5 agencies to collect additional information on case examples. Have you had an experience with field welding on a project that was or was not successful which could be used as a case example? *

○ Yes

○ No



LOGIC Hidden unless: Question "As a part of the synthesis, the project team will conduct a brief phone interview with 5 agencies to collect additional information on case examples. Have you had an experience with field welding on a project that was or was not successful which could be used as a case example?" #19 is one of the following answers ("Yes")

20. Please fill in the following information about a field welding project

Agency

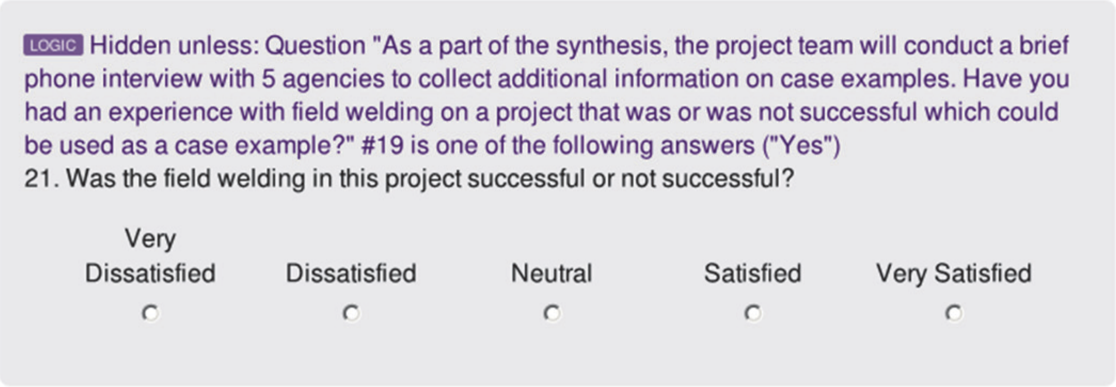
Contact name and contact information

Name of project

Location

Reason for field welding

Estimated number of welds



LOGIC Hidden unless: Question "As a part of the synthesis, the project team will conduct a brief phone interview with 5 agencies to collect additional information on case examples. Have you had an experience with field welding on a project that was or was not successful which could be used as a case example?" #19 is one of the following answers ("Yes")

21. Was the field welding in this project successful or not successful?

Very Dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied
○	○	○	○	○

APPENDIX C

Summary of Survey Results

TABLE C1
RESPONSES TO SURVEY QUESTION 1. DOES YOUR AGENCY ALLOW PLANNED FIELD WELDING REPAIRS/RETROFITS?

State	Yes/No	State	Yes/No
Alaska	Yes	Nebraska	Yes
Arizona	Yes	Nevada	Yes
Arkansas	Yes	New Hampshire	Yes
California	Yes	New Jersey	No
Connecticut	Yes	New Mexico	Yes
Delaware	Yes	New York	Yes
Florida	Yes	North Carolina	Yes
Hawaii	Yes	North Dakota	Yes
Idaho	No	Ohio	Yes
Illinois	No	Oregon	Yes
Indiana	No	Pennsylvania	No
Iowa	No	Rhode Island	Yes
Kansas	Yes	South Carolina	Yes
Kentucky	No	South Dakota	Yes
Louisiana	No	Tennessee	Yes
Maine	Yes	Texas	Yes
Maryland	Yes	Utah	No
Massachusetts	Yes	Vermont	Yes
Michigan	Yes	Washington	No
Minnesota	Yes	Wisconsin	Yes
Missouri	Yes	Wyoming	Yes
Montana	No		

TABLE C2
RESPONSES TO SURVEY QUESTION 2. WHY NOT?
(Question only available for response if answer to question 1 was "no")

State	Lack of Experienced Inspectors	Lack of Qualified Supervisors or Admin	Quality of Work	Unfamiliar With Appropriate Details	Past Issues	Expensive or Time Consuming	Unfamiliar With Process and/or Welding	Other (Please Specify)
Idaho			X					Note 1
Illinois			X		X			
Indiana				X			X	
Iowa	X		X		X			
Kansas								
Kentucky	X	X	X					
Louisiana	X	X	X		X			
Montana	X	X		X			X	
New Jersey			X					
Pennsylvania			X					Note 2
Utah		X	X	X			X	
Washington								Past performance
Wisconsin								
Wyoming								

Note 1: Welding to a member that is under stress/load.
Note 2: A structural bolted connection is preferred. Field welded repairs are only used as a last resort where there is no room to develop a bolted connection.

TABLE C3
RESPONSES TO SURVEY QUESTION 3. HAS YOUR AGENCY EVER PERFORMED PLANNED FIELD WELDING IN THE PAST?
(Question only available for response if answer to question 1 was "no")

State	Yes/No	State	Yes/No
Idaho	No	Nebraska	
Illinois	No	Nevada	
Indiana	No	New Hampshire	
Iowa	No	New Jersey	No
Kentucky	No	Pennsylvania	Yes
Louisiana	Yes	Utah	No
Montana	No	Washington	No

TABLE C4
RESPONSES TO SURVEY QUESTION 4. DOES YOUR AGENCY HAVE STANDARD PLANS, SPECIFICATIONS, PROCEDURES, OR DETAILS FOR CERTAIN FIELD WELDED REPAIRS?
(Question only available for response if answer to question 1 or question 3 was "yes")

State	Yes/No/Unknown	State	Yes/No/Unknown
Alaska	No	Nevada	Yes
Arizona	Yes	New Hampshire	Yes
Arkansas	Yes	New Mexico	Yes
California	Yes	New York	No
Connecticut	No	North Carolina	Yes
Delaware	No	North Dakota	No
Florida	No	Ohio	Yes
Hawaii	No	Oregon	No
Kansas	No	Pennsylvania	Yes
Louisiana	No	Rhode Island	No
Maine	Yes	South Carolina	Unknown
Maryland	No	South Dakota	No
Massachusetts	No	Tennessee	No
Michigan	Yes	Texas	No
Minnesota	No	Vermont	No
Missouri	Yes	Wisconsin	Yes
Nebraska	No	Wyoming	Yes

TABLE C5
RESPONSES TO SURVEY QUESTION 5. WAS THERE A GOVERNING SPECIFICATION OR WELDING CODE?
(Question only available for response if answer to question 1 or question 3 was "yes")

State	Always/Sometimes/ Never/Unknown	State	Always/Sometimes/ Never/Unknown
Alaska	Always	Nevada	Always
Arizona	Always	New Hampshire	Always
Arkansas	Sometimes	New Mexico	Always
California	Always	New York	Always
Connecticut	Always	North Carolina	Sometimes
Delaware	Always	North Dakota	Always
Florida	Unknown	Ohio	Always
Hawaii	Always	Oregon	Always
Kansas	Always	Pennsylvania	Unknown
Louisiana	Sometimes	Rhode Island	Always
Maine	Always	South Carolina	Sometimes
Maryland	Always	South Dakota	Always
Massachusetts	Always	Tennessee	Always
Michigan	Always	Texas	Always
Minnesota	Sometimes	Vermont	Always
Missouri	Always	Wisconsin	Always
Nebraska	Always	Wyoming	Always

TABLE C6
RESPONSES TO SURVEY QUESTION 6. WHAT WAS THE GOVERNING SPECIFICATION OR WELD CODE?
(Question only available for response if answer to question 5 was “always” or “sometimes”)

State	Response
Alaska	AWS D1.1 Structural Welding Code
Arizona	AASHTO/AWS D1.5 Bridge Welding Code
Arkansas	AASHTO/AWS D1.5 Bridge Welding Code
California	AASHTO/AWS D1.5 Bridge Welding Code
Connecticut	AWS D1.1 Structural Welding Code
Delaware	AASHTO/AWS D1.5 Bridge Welding Code
Hawaii	AASHTO/AWS D1.5 Bridge Welding Code
Kansas	AASHTO/AWS D1.5 Bridge Welding Code
Louisiana	AASHTO/AWS D1.5 Bridge Welding Code
Maine	AASHTO/AWS D1.5 Bridge Welding Code
Maryland	AASHTO/AWS D1.5 Bridge Welding Code
Massachusetts	AASHTO/AWS D1.5 Bridge Welding Code
Michigan	AASHTO/AWS D1.5 Bridge Welding Code
Minnesota	AASHTO/AWS D1.5 Bridge Welding Code
Missouri	Other (Combination of AASHTO/AWS D 1.5 and Internal Standard Specifications and Job Special Provisions)
Nebraska	AWS D1.1 Structural Welding Code
Nevada	AASHTO/AWS D1.5 Bridge Welding Code
New Hampshire	AASHTO/AWS D1.5 Bridge Welding Code
New Mexico	AASHTO/AWS D1.5 Bridge Welding Code
New York	Other (NYS Steel Construction Manual)
North Carolina	AASHTO/AWS D1.5 Bridge Welding Code
North Dakota	AASHTO/AWS D1.5 Bridge Welding Code
Ohio	AASHTO/AWS D1.5 Bridge Welding Code
Oregon	AASHTO/AWS D1.5 Bridge Welding Code
Rhode Island	AASHTO/AWS D1.5 Bridge Welding Code
South Carolina	AASHTO/AWS D1.1 Structural Welding Code
South Dakota	AASHTO/AWS D1.5 Bridge Welding Code
Tennessee	AASHTO/AWS D1.5 Bridge Welding Code
Texas	AASHTO/AWS D1.5 Bridge Welding Code
Vermont	AASHTO/AWS D1.5 Bridge Welding Code
Wisconsin	AASHTO/AWS D1.5 Bridge Welding Code
Wyoming	AASHTO/AWS D1.5 Bridge Welding Code

TABLE C7
RESPONSES TO SURVEY QUESTION 7. HAVE YOU PERFORMED THE FOLLOWING TYPES OF FIELD WELDED REPAIR/RETROFITS? CHECK ALL THAT APPLY.
(Question only available for response if answer to question 1 or question 3 was “yes”)

State	Fatigue Improvement[1]	Capacity Strengthening[2]	Corrosion/Impact Damage Strengthening[3]	Other (Please Specify)
Alaska		X	X	
Arizona	X		X	
Arkansas	X	X	X	
California	X	X	X	
Connecticut			X	
Delaware			X	
Florida			X	
Hawaii		X		
Kansas	X	X	X	
Louisiana			X	
Maine		X	X	
Maryland			X	
Massachusetts	X	X	X	
Michigan		X		
Minnesota			X	
Missouri	X	X	X	

(*continued on next page*)

TABLE C7
(*continued*)

State	Fatigue Improvement[1]	Capacity Strengthening[2]	Corrosion/Impact Damage Strengthening[3]	Other (Please Specify)
Nebraska			X	
Nevada	X		X	
New Hampshire		X	X	
New Mexico	X	X	X	
New York	X	X	X	
North Carolina	X	X	X	
North Dakota	X			
Ohio			X	
Oregon	X	X	X	
Pennsylvania		X	X	Note 1
Rhode Island	X	X	X	
South Carolina				Note 2
South Dakota	X	X	X	
Tennessee			X	
Texas	X	X	X	
Vermont		X	X	
Wisconsin	X	X	X	
Wyoming	X		X	

[1] Out-of-plane/distortion-induced cracking, etc.
[2] Ex. Adding cover plates to a rolled beam bridge.
[3] Ex. Repair/retrofit of damaged members.
Note 1: Field welded strengthening repairs have been commonly used to address corrosion of old steel truss bridges >90 years of age) especially on locally owned ones. The repairs are typically on the bottom chord as it is more susceptible to corrosion.
Note 2: Reconnect secondary members and add plates in compression zones.

TABLE C8
RESPONSES TO SURVEY QUESTION 8. WAS/IS FIELD WELDING PERFORMED BY IN-HOUSE STAFF OF WAS/IS IT CONTRACTED OUT?
(Question only available for response if answer to question 1 or question 3 was “yes”)

State	Response	State	Response
Alaska	Both	Nevada	Contracted out
Arizona	Contracted out	New Hampshire	Contracted out
Arkansas	Both	New Mexico	Contracted out
California	Contracted out	New York	Both
Connecticut	Contracted out	North Carolina	Both
Delaware	Contracted out	North Dakota	Contracted out
Florida	In-house	Ohio	Contracted out
Hawaii	Contracted out	Oregon	Contracted out
Kansas	Contracted out	Pennsylvania	Both
Louisiana	In-house	Rhode Island	Contracted out
Maine	Contracted out	South Carolina	In-house
Maryland	Contracted out	South Dakota	Contracted out
Massachusetts	Contracted out	Tennessee	Contracted out
Michigan	Both	Texas	Both
Minnesota	Both	Vermont	Both
Missouri	Both	Wisconsin	Both
Nebraska	Contracted out	Wyoming	Contracted out

TABLE C9
RESPONSES TO SURVEY QUESTION 9. WERE WELDERS CERTIFIED ACCORDING TO THE CONTROLLING WELDING CODE?
(Question only available for response if answer to question 1 or question 3 was “yes”)

State	Yes/No/Unknown	State	Yes/No/Unknown
Alaska	Yes	Nevada	Yes
Arizona	Yes	New Hampshire	Yes
Arkansas	No	New Mexico	Yes
California	Yes	New York	Yes
Connecticut	Yes	North Carolina	Yes
Delaware	Yes	North Dakota	Yes
Florida	Unknown	Ohio	Yes
Hawaii	Unknown	Oregon	Yes
Kansas	Yes	Pennsylvania	Unknown
Louisiana	Unknown	Rhode Island	Yes
Maine	Yes	South Carolina	Yes
Maryland	Yes	South Dakota	Yes
Massachusetts	Yes	Tennessee	Yes
Michigan	Yes	Texas	Yes
Minnesota	Yes	Vermont	Yes
Missouri	Yes	Wisconsin	Yes
Nebraska	Yes	Wyoming	Yes

TABLE C10
RESPONSES TO SURVEY QUESTION 10. WERE PLANS/SPECIFICATIONS PREPARED BEFORE THE WORK WAS PERFORMED?
(Question only available for response if answer to question 1 or question 3 was “yes”)

State	Always/Sometimes/ Never/Unknown	State	Always/Sometimes/ Never/Unknown
Alaska	Sometimes	Nevada	Always
Arizona	Always	New Hampshire	Always
Arkansas	Sometimes	New Mexico	Always
California	Always	New York	Always
Connecticut	Always	North Carolina	Sometimes
Delaware	Unknown	North Dakota	Always
Florida	Unknown	Ohio	Always
Hawaii	Always	Oregon	Always
Kansas	Always	Pennsylvania	Sometimes
Louisiana	Sometimes	Rhode Island	Sometimes
Maine	Always	South Carolina	Sometimes
Maryland	Sometimes	South Dakota	Always
Massachusetts	Always	Tennessee	Always
Michigan	Sometimes	Texas	Always
Minnesota	Sometimes	Vermont	Always
Missouri	Always	Wisconsin	Sometimes
Nebraska	Always	Wyoming	Always

TABLE C11
RESPONSES TO SURVEY QUESTION 11. WERE FIELD WELDING AND/OR INSPECTION PROCEDURES PREPARED BEFORE WORK WAS PERFORMED?
(Question only available for response if answer to question 1 or question 3 was “yes”)

State	Always/Sometimes/ Never/Unknown	State	Always/Sometimes/ Never/Unknown
Alaska	Sometimes	Nevada	Always
Arizona	Sometimes	New Hampshire	Always
Arkansas	Sometimes	New Mexico	Always
California	Always	New York	Always
Connecticut	Always	North Carolina	Sometimes
Delaware	Unknown	North Dakota	Sometimes
Florida	Unknown	Ohio	Never
Hawaii	Unknown	Oregon	Always
Kansas	Always	Pennsylvania	Sometimes
Louisiana	Unknown	Rhode Island	Always
Maine	Always	South Carolina	Sometimes
Maryland	Always	South Dakota	Always
Massachusetts	Always	Tennessee	Always
Michigan	Sometimes	Texas	Sometimes
Minnesota	Sometimes	Vermont	Always
Missouri	Sometimes	Wisconsin	Sometimes
Nebraska	Unknown	Wyoming	Always

TABLE C12
RESPONSES TO SURVEY QUESTION 12. WHICH OF THE FOLLOWING ITEMS WERE TYPICALLY INCLUDED IN THE FIELD PROCEDURES? CHECK ALL THAT APPLY.
(Question only available for response if answer to question 11 was “always” or “sometimes”)

State	Weld Procedures	Inspection Procedures	Welder Qualifications	Visual Inspect or Qualifications (QA/QC)	NDT Qualifications (QA/QC)
Alaska	X	X	X	X	X
Arizona			X		X
Arkansas	X		X		
California	X	X	X	X	X
Kansas	X	X	X	X	X
Maine	X	X	X	X	X
Maryland	X	X	X	X	X
Massachusetts	X	X	X		
Michigan	X		X	X	X
Minnesota	X	X	X	X	X
Missouri	X		X		X
Nevada	X	X	X	X	X
New Hampshire	X	X	X	X	X
New Mexico	X	X	X	X	X
New York	X	X	X	X	X
North Carolina	X		X		
North Dakota			X		
Oregon	X	X	X	X	X
Pennsylvania	X		X		
Rhode Island	X		X		
South Carolina	X	X	X	X	X
South Dakota	X	X	X	X	X
Tennessee	X	X	X		X
Texas		X	X		
Vermont	X	X			
Wisconsin	X		X		
Wyoming		X	X		

TABLE C13
RESPONSES TO SURVEY QUESTION 13. ARE WELDING INSPECTORS REQUIRED ON-SITE TO INSPECT FIELD WELDS?
(Question only available for response if answer to question 1 or question 3 was "yes")

State	Always/Sometimes/ Never/Unknown	State	Always/Sometimes/ Never/Unknown
Alaska	Sometimes	Nevada	Always
Arizona	Sometimes	New Hampshire	Sometimes
Arkansas	Never	New Mexico	Always
California	Always	New York	Always
Connecticut	Always	North Carolina	Sometimes
Delaware	Unknown	North Dakota	Never
Florida	Unknown	Ohio	Never
Hawaii	Unknown	Oregon	Always
Kansas	Always	Pennsylvania	Sometimes
Louisiana	Unknown	Rhode Island	Sometimes
Maine	Sometimes	South Carolina	Sometimes
Maryland	Sometimes	South Dakota	Sometimes
Massachusetts	Always	Tennessee	Always
Michigan	Unknown	Texas	Always
Minnesota	Sometimes	Vermont	Sometimes
Missouri	Never	Wisconsin	Unknown
Nebraska	Unknown	Wyoming	Always

TABLE C14
RESPONSES TO SURVEY QUESTION 14. IS NON-DESTRUCTIVE TESTING REQUIRED ON FIELD WELDS?
(Question only available for response if answer to question 1 or question 3 was "yes")

State	Always/Sometimes/ Never/Unknown	State	Always/Sometimes/ Never/Unknown
Alaska	Sometimes	Nevada	Always
Arizona	Always	New Hampshire	Always
Arkansas	Sometimes	New Mexico	Sometimes
California	Always	New York	Always
Connecticut	Always	North Carolina	Sometimes
Delaware	Unknown	North Dakota	Never
Florida	Unknown	Ohio	Sometimes
Hawaii	Sometimes	Oregon	Always
Kansas	Always	Pennsylvania	Sometimes
Louisiana	Sometimes	Rhode Island	Sometimes
Maine	Always	South Carolina	Sometimes
Maryland	Sometimes	South Dakota	Sometimes
Massachusetts	Sometimes	Tennessee	Always
Michigan	Always	Texas	Sometimes
Minnesota	Sometimes	Vermont	Always
Missouri	Sometimes	Wisconsin	Sometimes
Nebraska	Always	Wyoming	Always

TABLE C15
RESPONSES TO SURVEY QUESTION 15. ARE BASE METAL MATERIAL PROPERTIES DETERMINED PRIOR TO FIELD WELDING?
(Question only available for response if answer to question 1 or question 3 was "yes")

State	Always/Sometimes/ Never/Unknown	State	Always/Sometimes/ Never/Unknown
Alaska	Sometimes	Nevada	Always
Arizona	Always	New Hampshire	Always
Arkansas	Always	New Mexico	Sometimes
California	Always	New York	Always
Connecticut	Always	North Carolina	Sometimes
Delaware	Unknown	North Dakota	Never
Florida	Unknown	Ohio	Sometimes
Hawaii	Unknown	Oregon	Always
Kansas	Always	Pennsylvania	Sometimes
Louisiana	Unknown	Rhode Island	Sometimes
Maine	Always	South Carolina	Always
Maryland	Sometimes	South Dakota	Always
Massachusetts	Sometimes	Tennessee	Always
Michigan	Sometimes	Texas	Sometimes
Minnesota	Sometimes	Vermont	Sometimes
Missouri	Unknown	Wisconsin	Sometimes
Nebraska	Sometimes	Wyoming	Always

TABLE C16
RESPONSES TO SURVEY QUESTION 16. HOW WERE THE BASE METAL MATERIAL PROPERTIES TYPICALLY DETERMINED FOR WELDABILITY? CHECK ALL THAT APPLY.
(Question only available for response if answer to question 11 was "always" or "sometimes")

State	Shop Drawings	Mill Test Reports	Material Samples (Coupon Testing)	Using Date Built Information	Other (Please Specify)
Alaska	X		X		
Arizona				X	
Arkansas	X			X	
California			X	X	
Connecticut	X			X	Design drawings
Kansas	X	X	X		
Maine	X	X	X	X	
Maryland			X		
Massachusetts	X	X	X	X	
Michigan		X		X	
Minnesota		X	X	X	
Nebraska	X	X	X	X	
Nevada	X	X		X	
New Hampshire				X	
New Mexico				X	
New York	X		X	X	Note 1
North Carolina				X	As-built drawings
Ohio	X		X		
Oregon	X	X	X		
Pennsylvania			X	X	
Rhode Island	X		X	X	
South Carolina				X	Plans
South Dakota	X	X	X	X	
Tennessee	X		X		
Texas	X	X	X	X	
Vermont	X	X	X	X	
Wisconsin	X			X	
Wyoming				X	

Note 1: Contract plans (Mill Test Reports are not available on old bridges).

TABLE C17
RESPONSES TO SURVEY QUESTION 17. HAVE THERE BEEN ANY MAJOR PROBLEMS ASSOCIATED WITH THE REPAIRS/RETROFITS SPECIFICALLY RELATED TO THE FACT THAT THEY WERE FIELD WELDS?
(Question only available for response if answer to question 1 or question 3 was "yes")

State	Yes/No/Unknown	State	Yes/No/Unknown
Alaska	No	Nevada	No
Arizona	Yes	New Hampshire	No
Arkansas	No	New Mexico	Unknown
California	Yes	New York	No
Connecticut	No	North Carolina	Yes
Delaware	No	North Dakota	No
Florida	Unknown	Ohio	No
Hawaii	No	Oregon	No
Kansas	No	Pennsylvania	Unknown
Louisiana	Unknown	Rhode Island	No
Maine	No	South Carolina	No
Maryland	Yes	South Dakota	No
Massachusetts	No	Tennessee	No
Michigan	Unknown	Texas	No
Minnesota	No	Vermont	No
Missouri	No	Wisconsin	No
Nebraska	Unknown	Wyoming	No

TABLE C18
RESPONSES TO SURVEY QUESTION 18. WHAT WERE THE ISSUES? CHECK ALL THAT APPLY.
(Question only available for response if answer to question 17 was "yes")

State	Premature Cracking	Improper Welding	Quality Worksmanship[1]	Not Installed Per Plans/Specs	Other (Please Specify)
Arizona	X				
California			X	X	
Maryland	X	X			
North Carolina	X	X	X		

[1] Good workmanship practices not followed.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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