Nondestructive Evaluation of Steel Bridges: Methods and Applications

Kentucky Transportation Center Research Report — KTC-16-26/SPR14-485-1F
DOI: https://doi.org/10.13023/KTC.RR.2016.26

The Kentucky Transportation Center is committed to a policy of providing equal opportunities for all persons in recruitment, appointment, promotion, payment, training, and other employment and education practices without regard for economic or social status and will not discriminate on the basis of race, color, ethnic origin, national origin, creed, religion, political belief, sex, sexual orientation, marital status, or age.

Kentucky Transportation Center
College of Engineering, University of Kentucky Lexington, Kentucky

in cooperation with
Kentucky Transportation Cabinet
Commonwealth of Kentucky

KENTUCKY Transporation Center

Kentucky Transportation Center • University of Kentucky
176 Raymond Building • Lexington KY 40506 • 859.257.6898 • www.ktc.uky.edu

University of Kentucky

Research Report
KTC-16-26/SPR14-485-1F

Nondestructive Evaluation of Steel Bridges: Methods and Applications

Theodore Hopwood II, P.E.
Program Manager, Research

Christopher Goff
Transportation Technician II

Jared Fairchild
Transportation Technician II

and

Sudhir Palle, P.E.
Senior Research Engineer

Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, Kentucky

In cooperation with
Kentucky Transportation Cabinet
Commonwealth of Kentucky

December 2016

1. Report No. KTC-16-26/SPR14-485-1F	2.Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Nondestructive Evaluation of Steel Bridges: Methods and Applications		5. Report Date December 2016
		6. Performing Organization Code
7. Author(s) Theodore Hopwood II, Christopher Goff, Jared Fairchild and Sudhir Palle		8. Performing Organization Report No. KTC-16-26/SPR14-485-1F
9. Performing Organization Name and Address Kentucky Transportation Center College of Engineering University of Kentucky Lexington, KY 40506-0043		10. Work Unit No. (TRAIS)
		11. Contractor Grant No. SPR 14-485
12. Sponsoring Agency Name and Address Kentucky Transportation Cabinet State Office Building Frankfort, KY40622		13. Type of Report and Period Covered
		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Kentucky Transportation Cabinet, Federal Highway Administration, and U.S. Department of Transportation.

16. Abstract

Nondestructive evaluation (NDE) methods can be used to assess in-service steel bridges for problematic conditions caused by factors such as design, manufacturing, fabrication, and the service effects of traffic and corrosion. This report discusses typical NDE test methods used on bridges, including penetrant testing, magnetic particle testing, eddy current testing, ultrasonic testing (including phased array testing), radiography, and acoustic emission testing. NDE operations such as flaw location, characterization, and sizing are covered as well. Results of a national survey of departments of transportation's (DOTs) use of NDE are presented. A simple procedure for using NDE to address DOT bridge concerns is proposed along with a risk-based inspection approach to scheduling/scoping bridge inspections.

17. Key Words acoustic emission testing, bridge inspection, crack detection, defects, eddy current testing, flaws, magnetic particle testing, nondestructive evaluation, phased array ultrasonic testing, radiography, steel bridges, ultrasonic testing, welds		18. Distribution Statement Unlimited with the approval of the Kentucky Transportation Cabinet	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 114	22. Price

Table of Contents

List of Figures

List of Tables

Acknowledgements

The authors would like to thank Joshua Rogers of the Kentucky Transportation Cabinet who served as the Chairperson for this study and David Steele who served as the Co-Chairperson.

Appreciation is also extended to the Transportation Research Board AHD 37 Bridge Preservation Subcommittee and especially Bruce Johnson of the Oregon Department of Transportation for interfacing with AASHTO in support of the survey of state DOTs on their use of nondestructive evaluation to inspect steel bridges.

Executive Summary

This report addresses the field application of nondestructive evaluation (NDE) methods to assess flaws in elements of the Kentucky Transportation Cabinet's (KYTC) in-service steel bridges. KYTC has approximately 1,050 steel bridges in its inventory. These bridges have steel superstructures; it is possible a few bridges have steel bents for substructures. The average age of those bridges is 47 years, nearly equal to their 50-year design life. As these bridges age, the cumulative effects of structure loading, the environment and service practices (e.g., deferred maintenance due to inadequate funding, the application of deicing chemicals) will result in the continued deterioration of their structural steel elements.

NDE is an important tool that DOTs can use to address problematic issues in steel bridges that threaten their structural integrity. NDE encompasses several methods, which are used to search for and detect potential flaws, characterize them (as to type/activity) and perform flaw sizing.

Bridge steel is usually made from steel ingots or continually cast slabs that are rolled into plates, bars, and various structural shapes. Semi-finished pieces can contain imperfections in the material which, if not removed, may be present in the finished pieces. Those may be harmful depending the nature of the flaw and upon subsequent fabrication operations and use in service. Steel-making/finishing flaws can include surface defects: scabs, slivers, laps, and seams; also subsurface flaws including stringers, inclusions, and porosity. Steel fabrication shops are locations where flaws in steel plates and shapes can be detected and repaired during processing (e.g., edge preparation for plates). Welding that occurs in fabrication shops can introduce flaws/defects in bridge steel weldments (e.g., notches, slag inclusions, porosity, cracks, lack of fusion and lack of penetration). These must be detected and repaired before the steel leaves the shop. Other extraneous flaws that can be introduced arc strikes and tack welds, which may not be eliminated after fabrication. Both of these flaws can also be introduced during construction.

Steel and earlier ferrous bridge metals are susceptible to atmospheric corrosion. Corrosion can be exacerbated by deck runoff and traffic-generated aerosols that contain deicing salts. This can result in general corrosion, causing loss-of-section of bridge components and higher dead and live stresses and stress concentrators that may contribute to future cracking problems. Corrosion can also freeze pins or hangers in pin-and-hanger connections and cause them to fracture.

In normal atmospheric environments, steel bridge components can crack for a variety of reasons related to design, manufacture, fabrication, construction and service exposure. The latter can include live and dead loading, vehicle impacts and, potentially, wind and thermal loadings. Steel bridges can contain cracks that are benign — typically the result of manufacturing or fabrication errors. These types of cracks can appear to be problematic and sometimes require significant investigations to demonstrate they are not a physical threat to a bridge.

More serious crack problems arise when previously benign cracks grow, or are nucleated and grow due to the actions of fatigue, stress corrosion and corrosion fatigue. Under live stresses, flaws in common structural steel can transform into growing fatigue cracks. High-strength steels (e.g., wires or improperly heat-treated steel plates) can be subject to stress corrosion cracking that can occur under static tensile loading. Common structural steels can also experience crack growth due to a combination of corrosion and alternating stresses — corrosion fatigue — where either of those mechanisms acting separately would not be problematic.

The most widely used NDE method for all bridge components (including those made from steel, reinforced concrete, wood or a combination of those materials) is visual inspection or visual testing (VT). However, VT generally limits inspection to surface flaws that are sufficiently pronounced. While VT can be used for a range of bridge components/materials, there is a variety of NDE equipment that can provide enhanced evaluations of those. Some NDE methods require minimal equipment and operator knowledge for

successful application. Those are commonly used by bridge inspectors and engineers. Other NDE methods require extensive operator knowledge and expertise, requiring their application by trained NDE specialists.

NDE methods detect and characterize flaws in materials (e.g., steel). To do this, they provide some type of indication to the test operator that shows a change in condition compared to the bulk of the material. The operator must interpret that indication and determine whether it is a flaw, the type of flaw (if possible) and whether that flaw is a defect. The latter judgement may lie outside the expertise and authority of the test operator.

Common NDE methods are grouped into two categories: external (surface) and internal (subsurface). Some can address both surface and subsurface flaws. Magnetic particle testing can detect both external and subsurface flaws if they are not too deep. Ultrasonic testing can be used to detect some surface-breaking flaws. There are many NDE options available for use on bridges. However, six NDE methods are typically used for common steel bridge inspection tasks:

- Penetrant testing (PT)
- Magnetic particle testing (MT)
- Eddy current testing (ET)
- Radiographic testing (RT)
- Ultrasonic testing (UT)
- Acoustic emission testing (AET)

PT, MT and ET are typically considered external/surface test methods. RT and UT are considered internal tests. AET is used for flaw presence and location based upon flaw dynamic activity (e.g., crack growth). This report describes the operational characteristics of each method.

In 2016, KTC prepared a survey to state DOTs that asked them to identify: 1) their practice and use of NDE to inspect bridges and 2) how NDE findings are incorporated into their decision-making process. The survey was distributed to all DOTs, with the assistance of AASHTO. The detailed survey summary is provided in the Appendix. Thirty-one DOTs responded to the survey, although the number of responses received for individual questions varied significantly.

A five-phase process is proposed to address the use of NDE to specific DOT concerns about the reliability of steel bridges. Those are:

- Identify a problem or concern
- Determine effective NDE methods/test personnel to address the concern
- Apply NDE on the pertinent bridge/structural member in a timely manner
- Interpret the NDE findings
- Develop a remedial action (if warranted)

KYTC currently employs NDE in a manner similar to most DOTs. District bridge inspectors carry PT and/or MT supplies/equipment and can use them to test for surface defects. Also, UT, RT and AE have been used to evaluate or size flaws both on an as-needed basis and on inspection and experimental projects using several private consultants and university research centers. KYTC has reviewed NDE findings to make the appropriate repair decisions.

Other industries (e.g., petroleum and aviation) are adopting risk based inspections (RBI) as the basis to inspect their assets. Risk can be defined as:

Risk = Probability of Event x Consequences of Event

For bridges, the probability of the event can be the probability of loss of service and ensuing motorist inconvenience due to delays or detours or, in the worst case, the probability of structure collapse and loss of life. The former is more common and can be very expensive if user costs are incorporated into the total cost of an incident. The latter constitutes a low-probability high-consequence event. Both costs need to be factored into risk assessments. In 1984, the University of Kentucky Transportation Research Program (antecedent to the Kentucky Transportation Center) published a report addressing risk factors for bridges, using those to financially justify expenditures for using NDE methods to reduce those risks.

Using Reliability-Based Bridge Inspection Practices, rather than performing inspections at 24-month intervals, focuses on the safety and reliability of bridges by determining appropriate inspection practices for bridges that consider the structure type, age, condition, importance, environment, loading, prior problems, and other bridge characteristics. The appropriate use of NDE should be part of a RBI approach, including its potential for lowering risks.

As the KYTC bridge inventory (not just steel bridges) ages, problems stemming from cumulative service damage will increase. Sufficient funds will not be available to replace most existing bridges, and they will need to remain in service for decades to come, many beyond their original design service lives. NDE will need to be an integral part of bridge preservation and maintenance programs as it can help ensure that bridges retain their structural integrity and continue to safely serve the public. Nationwide, the concept of risk management is becoming more prominent, and viable approaches to RBI have been formulated. At some point, DOTs will begin to adopt risk-based bridge inspections incorporating NDE.

The following steps are recommended.

- Offer formal training to KYTC inspectors who use PT and MT from firms primarily involved in NDE training.
- Maintain a rapid respond "first look" NDE capability either through KTC or outside consultants.
- Investigate the development of a risk-based inspection program focusing on both inspection frequency and enhanced inspection (NDE) tools.

1. Introduction

The FHWA defines nondestructive evaluation (NDE) as, "…a means of analyzing and assessing the condition of various structural components in service highway infrastructure assets—pavement, bridges, and tunnels—without impairing their future usefulness (1)." This report addresses the field application of NDE methods to assess flaws in elements of Kentucky Transportation Cabinet (KYTC) in-service steel bridges. Its focus is on steel structures, primarily of steel plates and rolled shapes, although there are brief discussions concerning other common bridge components such as pins and steel wires. A follow-up project, KYSPR 15-505 *Nondestructive Evaluation of Reinforced Concrete*, will address field testing of structural concrete on bridges. The NDE methods discussed in this document are primarily for inspections where inspection personnel/NDE operators are performing on-site (field) tests, though analysis of results may occur off-site (e.g. reading radiograph film/images). One exception is *acoustic emission testing* which can also be considered a long-term structural health monitoring test depending upon how it is employed. Visual inspection or visual testing (VT) is commonly considered an NDE method. In this document, the term *nondestructive evaluation* is primarily used to describe enhanced methods of inspection that are employed to augment VT and, in some cases, replace it where it does not work (e.g. subsurface indications or corrosion section loss measurements of gusset plates).

This report's recommendations are informed in part by a national survey of DOT practices. KYTC engineers, inspectors and managers can use this report in their efforts to determine if nondestructive evaluations are warranted for specific bridge components, and examine and select from available NDE methods — their functions/uses and common bridge component applications. Additionally, this document addresses some instances where NDE may not practical and describes some options for tackling them. Rather than emphasizing or assessing technical aspects of the various applicable NDE methods in depth, this document seeks to provide KYTC bridge maintenance officials with recommendations for applying NDE to the inspection of steel bridges (primarily plate structures) and determining a course of action based upon NDE findings, from initial concern to resolution. It briefly touches on the use of NDE to address specific concerns and also its potential broader use to facilitate risk-based inspections during KYTC routine safety inspections.

The following definitions are provided based upon ASTM E 1316 *Standard Terminology for Nondestructive Examinations*:

<u>Defects</u> — one or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable. *A defect in a bridge impacts its serviceability and can lead to postings, closures or possibly structural collapse.*

<u>Discontinuity</u> — a lack of continuity or cohesion; an intentional or unintentional interruption in the physical structure or configuration of a material or component.

<u>Flaw</u> — an imperfection or discontinuity that may be detectable by nondestructive testing and is not necessarily rejectable.

<u>Imperfection</u> — a departure of a quality characteristic from its intended condition.

<u>Indication</u> — what the specific NDE method reveals. The test operator first determines whether it is relevant or irrelevant. If it is relevant, the operator then determines whether it is a defect. Sometimes that interpretation is made by others.

1.1 Background

KYTC has approximately 1,050 steel bridges in its inventory. Those bridges have steel superstructures, and it is possible that a few bridges have steel bents as substructure elements. The average age of those bridges is currently 47 years, almost equal to their 50-year design life (2). As these bridges age, the cumulative effects of structure loading, environment and service practices (e.g., deferred maintenance due to inadequate funding, the application of deicing chemicals) will result in structural steel elements progressively deteriorating (i.e., wear and tear or "damage"). KYTC bridges are evaluated periodically to determine whether deterioration has occurred that requires follow-up corrective actions. In some cases, design, materials, fabrication or construction problems are detected that may or may not interact with the aforementioned service-related deterioration mechanisms to create greater levels of deterioration. In some instances, the overall impacts of those findings also must be evaluated to determine whether immediate corrective actions are warranted.

Nondestructive evaluation (NDE) is an important tool that helps DOTs address problematic issues that occur in steel bridges and threaten their structural integrity. NDE can involve the assessment of indications by several NDE methods, searching for potential flaws, flaw detection, flaw characterization and flaw sizing. The following commentary includes an overview of common NDE methods, operator factors, their use and limitations and specific situations where KYTC officials can use them to assist with decision making. It presents recommendations for KYTC in applying NDE. However, it does not serve as official KYTC policy on when to apply them or on how to use the resulting findings.

1.2 Bridge Design Flaws

Steel bridge designs have evolved over the years, and modern designs have incorporated changes to eliminate many design issues that negatively impacted earlier structures. The main source of many steel bridge problems — excluding corrosion — relates to the emergence of welding for fabricating bridge components. This resulted in new concerns for bridges due to the possibility of weld defects that could replicate cracks and short-circuit anticipated service lives. Primary design problems are related to: 1) abrupt section changes, 2) re-entrant corners, 3) poor weld designs (impacting residual stresses and subsequent fracture behavior), 4) lamellar tearing and 5) overuse of non-redundant designs (Figure 1). Bridges using riveting have experienced cracking problems as well, typically after years of service.

(a) (b)

Figure 1 Cracking in I-75 twin bridges over Lynn Camp Creeks: (a) SB bridge in 2012 and (b) NB bridge in 2014 due to a poor weld design.

1.3 Bridge Steels

Steels and wrought/cast irons used in early truss bridges were typically proprietary. Standardization of bridge steels did not occur until 1901, when ASTM A7, *Specification for Steel for Bridges and Buildings*, was issued. Common ASTM standard bridge steels now include low-carbon steels (e.g. ASTM A7, A373 and A36), high-strength low alloy steels (ASTM A242, ASTM A441, ASTM A572, ASTM A588 and ASTM/AASHTO A709/A709M grades 50 and 50W) and high-strength structural steels (US Steel T-1 and other proprietary alloys, ASTM A 514, ASTM A 517 and ASTM/AASHTO A709/A709M – grades 70 and 70W, 100 and 100W).

The most widely used steels in KYTC bridges are likely low-carbon steels. High-strength low alloy weathering steels — ASTM A588 and ASTM/AASHTO A709/A709M grade 50W — have been used in KYTC bridges in both unpainted and painted applications. For about the past 10 years, KYTC has used only the ASTM/AASHTO A709/A709M grade 50W steel. High-yield strength quenched-and-tempered structural steels, both proprietary and standard ASTM types, have been used in the past on long-span KYTC bridges, but that type of steel has not been used frequently, if at all, in recent years.

Bridge steel is usually made from steel ingots or continually cast slabs that are rolled into plates, bars, and various structural shapes. These semi-finished pieces may contain imperfections in the material which, if not removed, may be present in the finished pieces. Imperfections may be harmful depending on the nature of the flaw and the subsequent fabrication operations and use in service. Steel-making/finishing flaws include surface defects, such as scabs, slivers, laps, and seams, and subsurface flaws, including stringers, inclusions and porosity. Scabs are irregularly shaped, flattened protrusions caused by mill operations (Figure 2). They typically appear as round or oval surface blemishes. They can have scale underneath them that may eventually produce cracking in a material. Slivers (or fins) are elongated pieces of metal attached to the base metal at one end. They can be bent up by abrasive blasting operations during bridge painting. Laps are folds in the metal that appear to be seams running along the steel plate. Seams are open, broken lines that run along the length of the metal and are caused by the presence of scale as well as from the roughness of mill rolls. Inclusions are non-metallic impurities introduced during the steelmaking process. These are flattened during the rolling process; they form flat (planar) laminations that can result in tearing problems for certain weldment designs. Porosity can be present internally. With rolling and continuous casting, cracks (surface and internal) are possible. In addition to geometric defects, improper steel processing can result in metallurgical problems, such as banding or brittle steel microstructures (3, 4).

Steel fabrication shops are locations where flaws in steel plates and shapes can be detected and repaired during processing (e.g., edge preparation for plates). Some steel manufacturing flaws are considered acceptable and not repaired. Also, fabrication shops employ welding which can introduce flaws/defects in bridge steel weldments (e.g., notches from poor fit-ups or welding processes, slag inclusions, porosity, cracks, lack of fusion and lack of penetration). Fabrication shop errors may result in repairs that are unsuccessful and introduce flaws/defects in the steel. Those must be detected and repaired before the steel leaves the shop. Shops have quality control (QC) NDE personnel to perform the final inspections and KYTC has quality assurance (QA) personnel that review shop NDE results.

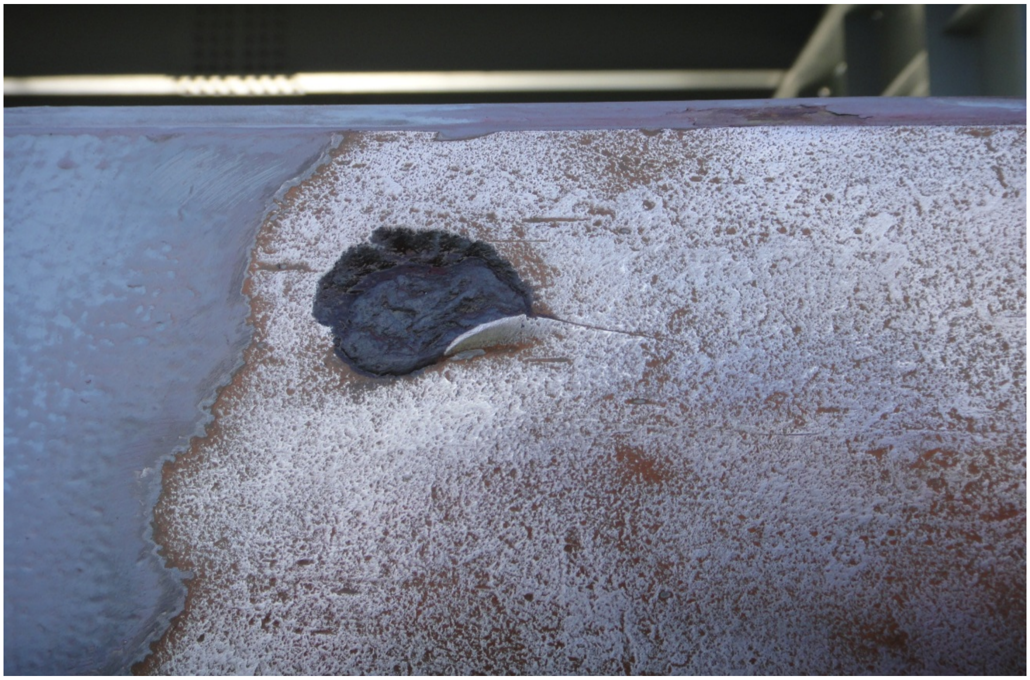


Figure 2 Scab in steel plate on bridge tie chord

1.4 Common Types of Bridge Steel Damage

KYTC has the following types of steel bridges in its inventory:

- Deck girder bridges (most common)
- Deck truss bridges
- Orthotropic bridges
- Pony truss bridges
- Pony girder bridges
- Through truss bridges
- Tied arch bridges
- Rigid frame bridges
- Suspension bridges
- Cable-stayed bridges

Most of the larger steel bridges spanning major waterways possess fracture-critical (non-redundant) members (FCMs) that are the typical focus of NDE inspections. Occasionally, shorter span bridges have FCMs (Figure 3). The failure of an FCM could result in a bridge collapsing or becoming severely crippled, rendering it unusable. Generally, extreme caution is exercised if a crack is found on a fracture-critical member. This often results in temporary closure or a load posting that could significantly restrict traffic over the bridge. (Figure 4). Redundant bridges will not collapse if a major structural member (e.g., beam, girder of a deck girder bridge) contains major defects or fails. However, a defected or failed structural member will usually reduce the bridge's load carry capacity and result in significant motorist inconveniences.

Steel bridges can have problems manifested as: 1) corrosion, 2) cracking, 3) wear, 4) distortion or 5) surface blemishes or a combination of those. Singly or combined, they can be caused by several factors, which are the root cause(s) of those five problems. A simple repair may eliminate a problem (e.g., drilling a check-hole to stop crack growth), however, in all likelihood the cracking's root cause should be addressed to permanently resolve the concern about cracking in similar sites on a bridge (and similar ones on other bridges). Bridge inspectors occasionally encounter surface conditions on steel that result from fabrication or construction and which they cannot assess by readily available means. Those may require additional evaluations and possibly expert analyses.

Figure 3 Simple span non-redundant deck girder approach spans that are fracture-critical

Figure 4 I-275 Northbound bridge over the Ohio River temporarily posted at 6,000 lbs for trucks due to a cracking problem in 2008

1.4.1 Corrosion

Steel, as well as earlier ferrous bridge metals, is susceptible to atmospheric corrosion. Deck runoff and traffic-generated aerosols that contain deicing salts can exacerbate corrosion. This can result in general corrosion, causing loss-of-section of bridge components and higher dead and live stresses and stress concentrators, which may contribute to future cracking problems. Corrosion can also impact freeze pins or hangers in pin-and-hanger connections, causing them to fracture. Today, general corrosion is probably the most common problem found on steel bridges.

Instances of corrosion cracking are relatively infrequent on bridges. In some cases, steel bridge components subjected to live loads are exposed to immersion for extended periods, resulting in corrosion fatigue cracking. Steel manufacturing problems can also contribute to stress corrosion cracking of high yield strength quenched-and-tempered steels. Wires in suspension bridge cables, vertical hangers (wire ropes or helical strand), prestressing strand and post-tensioning strand are particularly vulnerable to corrosion and corrosion cracking.

1.4.2 Cracking

In normal atmospheric environments, steel bridge components can crack from a variety of causes related to design, manufacture, fabrication, construction and service exposure. The latter can include live and dead loading, vehicle impacts and, potentially, wind and thermal loadings (Figure 5). Cracking in steel bridge components typically occurs at joints, connections, or locations with geometric discontinuities. Cracks are commonly oriented transverse to existing or applied tensile loads (stresses), but can also occur parallel to them (tearing or out-of-plane cracking). Stresses typically result from fabrication (welding/forming as residual stresses) or in-service as existing or applied stresses. Steel bridges can contain cracks that are benign — typically the result of manufacturing or fabrication. Those types of cracks can appear to be problematic and sometimes require significant investigations to demonstrate they are not a physical threat to a bridge.

More serious crack problems arise when previously benign cracks grow or are nucleated and grow due to the actions of fatigue, stress corrosion and corrosion fatigue. Under live stresses, flaws in common structural steel can turn into growing fatigue cracks. High-strength steels (e.g., wires or improperly heat-treated steel plates) can undergo stress corrosion cracking that occurs under static tensile loading. Common structural steels can also experience crack growth under a combination of corrosion and alternating stresses — corrosion fatigue — where either of those mechanisms acting separately would not be problematic. Those types of cracking are typically termed sub-critical crack growth, meaning the cracks will not cause component failure until they reach a critical size. At that point, the steel component will typically experience an unstable fast fracture (e.g., brittle cracking). While the rates of crack growth may be slow, the critical crack size for component failure is difficult to assess.

Critical crack size depends upon the magnitude and orientation of live and dead load stresses, residual stresses (from welding), steel toughness (at minimum service temperatures), steel component thickness and structural detailing. In many bridge situations, the critical crack sizes in steel components are sufficiently large to enable their practical detection by visual inspection or NDE methods well before a bridge component fractures. In a limited number of circumstances, no sub-critical crack is present before fast fracture or it may be too small to be reliably detected by most NDE methods. In those cases, remedial actions are required in lieu of NDE.

KYTC inspectors are required to perform arm's length visual inspections of FCMs annually. Redundant bridge members (commonly beams or girders on deck girder bridges) are inspected every other year. Some inspections of steel bridge members may not be at arm's length. For those, bridge inspectors need to be aware of situations where cracking may occur due to fatigue or fracture-prone details, transverse attachments of lateral bracing or skewed structures that may prove problematic. Those locations should be inspected at arm's length periodically using ladders, lift buckets, man lifts or under-bridge access vehicles to ensure that no cracking has occurred.

As previously noted, welding is a common source of cracking. Cracks can occur transverse to or along welds. Typically, current fabrication shop QC/QA procedures have proven effective in preventing any weld cracks from reaching the field, but there remains the remote possibility that a crack can be missed. Historically, some of the earliest welded steel bridges, especially those using high yield strength quenched-and-tempered steel, had significant numbers of cracks in welds of FCMs (e.g. the I-65 John F. Kennedy Memorial Bridge in the early 1990s, and the I-64 Sherman Minton Bridge in 2011). In those instances, most of the cracks were on structural members having low live stresses where fatigue crack growth was not a concern. There was significant concern in both cases that the cracking might pose the threat of brittle fractures due to a reduction in crack tolerance (i.e., steel toughness) at lower temperatures. That concern led to the temporary closure of the I-64 Sherman Minton Bridge by the Indiana DOT for crack repairs in 2011. Welded structural members are monolithic, allowing an unstable crack to propagate and sever the entire component and, for an FCM, possibly lead to a bridge collapse.

Fabrication shop cracking of welds, if not detected and repaired prior to construction, poses significant problems in bridges as they experience live loads/stresses that can promote rapid fatigue crack growth since a crack is already in place and has some size (Figure 6). The weldments may also possess residual stresses that promote unstable/fast fracture. The effect of those factors is to establish a finite service life for a structural component well below any projections made for its initial design. Other shop flaws that can prove problematic include: lack of penetration, lack of fusion, slag inclusions, cluster porosity, arc strikes, and weld undercuts. Weld repairs and tack welds (sometimes applied during construction) can also result in shop cracking of bridge components.

Structural details such as joints or connections are common locations where cracking can occur. Welding is used to connect attachments, cover plates and as stiffeners to main structural components (e.g. beams, chord members and girders). In the past, those items sometimes have suffered from poor detailing and shop fabrication practices. Some attachments provide geometric discontinuities (e.g., ends of horizontal stiffeners) that offer low resistance to fatigue cracking. Other problematic weld details involve narrow spacings between attachment welds (e.g., Hoan Bridge details) and overlapping welds that can promote cracking in the shop or field. Some of those fractures can be entirely brittle or have small critical crack sizes for unstable cracking. In those cases, a bridge inspector must be able to recognize their presence on a bridge and seek remedial solutions rather than completely rely on NDE.

Older steel and iron bridges used riveted construction. That typically includes KYTC bridges built prior to about the mid-1950s and some built into the early 1960s with mixed designs also incorporating welding or bolting. The bridge components were fabricated from plates, angles, channels and bars connected by rivets in punched holes. Riveted connections can sometimes experience fatigue cracking where high stress ranges or unusual load transfer occurs (5). Riveted structural members have lower fatigue tolerances than those made using bolts in drilled and reamed holes. They can experience fatigue cracking with the cracks running from under rivet heads and generally oriented transverse to the applied stress. Because riveted structural members are composite members consisting of multiples plates and angles (rather than monolithic like welded plate members), they may be more resistant to failure when cracking occurs compared to welded members.

A number of other issues can occur with other non-welded steel bridge components including cracking of eyebars, hangers and bridge pins (Figure 7).

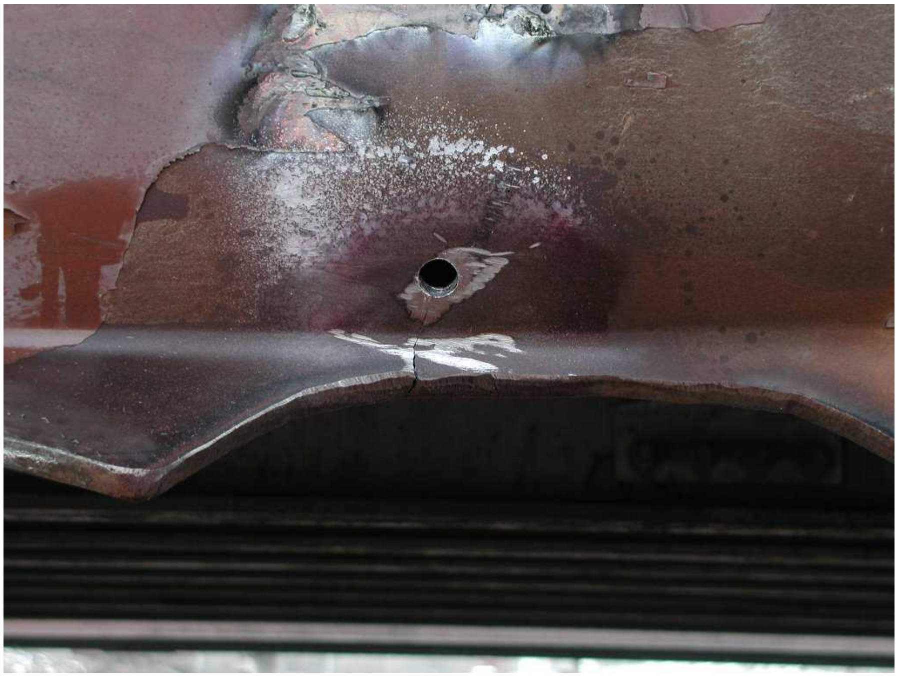
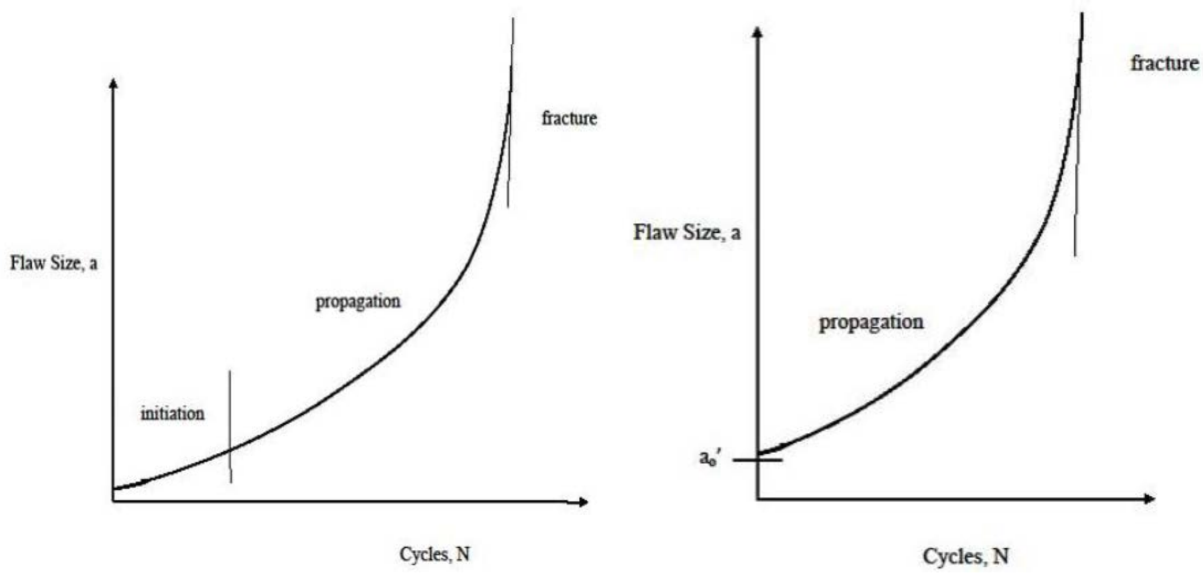


Figure 5 Crack caused by vehicle impact (Asfour, S., Emergency Bridge Repairs, Presentation at the Midwest Bridge Working Group Meeting, Evanston, IL, 2005)



(a) (b)

Figure 6 Fatigue crack growth: (a) Crack is nucleated and grows toward failure, (b) Pre-existing crack grows toward failure, removing the need for load cycles for crack nucleation ("Steel Bridge Design Handbook – Design for Fatigue," FHWA, Report No. FHWA-iFi12-052-Vol. 12, 2012)

Figure 7 Fractured Hanger

1.4.3 Wear

In some cases small movements can cause fretting, which leads to one component cutting into a mating part, such as plate cutting into a pin (Figure 8). Wear between pin and links can elongate pin-holes and result in unintended engagement forces between the truss knee, pins and links that might prove problematic in the future. While wear may not be a problem, its impact on pins, links, hangers, and other components may warrant periodic NDE.

Figure 8 Top chord plate wearing groove into a top chord pin on the K-65 Kennedy Bridge over the Ohio River at Louisville

1.4.4 Distortion

There are several types of distortion that can occur, including web crippling (Figure 9). Welded steel bridge girders are susceptible to distortion-induced fatigue cracking. These cracks develop near or at connections between girders and out-of-plane elements (Figure 10). It is estimated that 90% of all fatigue-related cracks in bridges have arisen due to out-of-plane distortion. Distortion also occurs where rust forms between faying steel components (e.g., pack rust on built-up riveted steel members).

Figure 9 Web crippling of a corroded girder

Figure 10 Distortion-induced fatigue crack in bridge beam

1.4.5 Surface Blemishes

Inspectors occasionally encounter surface flaws such as slivers, scabs, arc strikes and dents or gouges. For the most part, these may be ignored, but some can be problematic (e.g., arc strikes) and require periodic inspection or repairs (Figure 11).

Figure 11 Welding arc strike on surface of steel plate (Heavy Engineering Research Association, Auckland, NZ.)

1.5 The Roles of Inspectors and NDE Specialists in Performing Bridge Inspections

Visual inspection or visual testing (VT) is the NDE method most widely used by bridge inspectors for all bridge components including those made from steel, reinforced concrete, wood or a combination of those materials. However, it generally limits inspection to surface flaws that are sufficiently pronounced to be noticeable. They must be detected and interpreted by an inspector who may also be concerned with other tasks, including rating bridge elements, traffic on the bridge or working at heights. Working under marginal lighting conditions also poses challenges. Those limitations are disadvantageous when trying to accurately evaluate a bridge component for a known or suspected flaw, or to determine whether a flaw should be characterized as a defect that requires follow-up action. Proper access and lighting are external factors necessary for good visual inspections (Figure 12).

Ideally, conventional bridge inspections should be performed by people having certain physical and psychological attributes. They must have good vision, a reasonable level of comfort in the work environment and be willing to perform tedious tasks for extended periods. They must have technical knowledge of the structural elements they are inspecting, some insight into potential deterioration mechanisms and visual indications of those along with some idea of their potential severity. Bridge inspectors also must have good verbal and writing skills to communicate their findings.

While VT can be used for a range of bridge components/materials, a variety of NDE equipment can provide enhanced evaluations. Operators of NDE equipment should have the same types of skills possessed by bridge inspectors plus specialized knowledge of their test methods and equipment, how they are used to inspect generic details (e.g., welds) and how the resulting indications are interpreted for proper evaluation of a test piece. In some cases, the NDE operators may lack experience with bridge components and therefore need assistance from knowledgeable bridge inspectors or engineers to properly apply their test methods or interpret the resulting indications. Some NDE methods require minimal equipment and operator knowledge for successful application. Those are commonly used by bridge inspectors and engineers. Other NDE methods require extensive operator knowledge and expertise, requiring their application by trained NDE specialists. Operator factors significantly influence test results (see Table 1). They must be reasonably comfortable in their work environment to provide the best results. In a recent major bridge NDE project, ultrasonic test operators were required to detect flaws in test plates in the bridge environment to ensure that the surroundings did not hamper their ability to correctly perform the tests (Figure 13).

Table 1 Factors Affecting NDE Proficiency — from Boisvert et al. (5)

Human	Physical
Dexterity	Environment
Formal Training	Inspection Rate
Cognition	NDE Method
Psychomotor Skill	Flaw Size & Density
Rational Ability	Part Geometry
Motivation	

The decision to use an NDE method can be simple or complex. Bridge inspectors can take inspection materials and use simple equipment to perform common tests to detect surface breaking defects (e.g., cracks) during routine biennial inspections or annual fracture-critical inspections. In other instances, detailed reviews are made to determine suitable NDE methods, test procedures and the qualifications of test operators. In some cases, several NDE methods/operators are used to confirm the presence of a flaw in steel and assess its severity. In contrast to these NDE test extremes, there are circumstances where no NDE methods are satisfactory and other actions are required.

Regardless of the use of an NDE method, some supervisory decision making is ultimately required. Use of NDE should incorporate the best methods possible to assess the condition of structural elements, leading either to a decision for follow-up actions (e.g., repairs, load restrictions, follow-up inspections) or elimination of concerns (e.g., a do-nothing decision). If the test results indicate no further actions are needed, there is still benefit because the testing will reduce risk. No testing is absolutely perfect, but application of the most appropriate NDE methods, properly applied and interpreted, will reduce residual risks to a low level, practically eliminating concerns that existed prior to their use. In some cases, where NDE shows no current flaws, a decision may be made to periodically retest to detect growing fatigue cracks that were not present during the initial test or were too small to be detected. Using capable, reliable NDE operators is critical for setting up a test properly, acquiring data, and interpreting test results. The interfacing of the NDE operator and the engineer in charge of decision making is critical.

Figure 12 Good visibility is necessary for visual inspection

Figure 13 NDE operator being qualified using flawed plates attached to bridge tie-chord (Gorrill, G., "Sherman Minton Rehabilitation, Presentation to the Midwest Bridge Working Group, Schaumburg, IL, May 30, 2012)

2. Nondestructive Evaluation Methods for Steel Bridges

2.1 Flaws

With respect to nondestructive testing, flaws are classified as external (surface) (Figure 14) or internal (subsurface) (Figure 15). For common steel bridges made from rolled shapes and plates, external flaws of concern are typically cracks that appear as linear indications on the surfaces of steel components. These may or may not be readily observable by VT. Internal flaws do not appear on the surface and therefore are undetectable by visual inspection. Flaws can also be classified as planar (e.g., cracks or crack-like welding flaws — lack of penetration or lack of fusion or laminations) or volumetric (e.g., porosity or slag inclusions). Planar flaws may be external or internal, and those that break the surface are typically detected as linear indications. Volumetric flaws are typically internal.

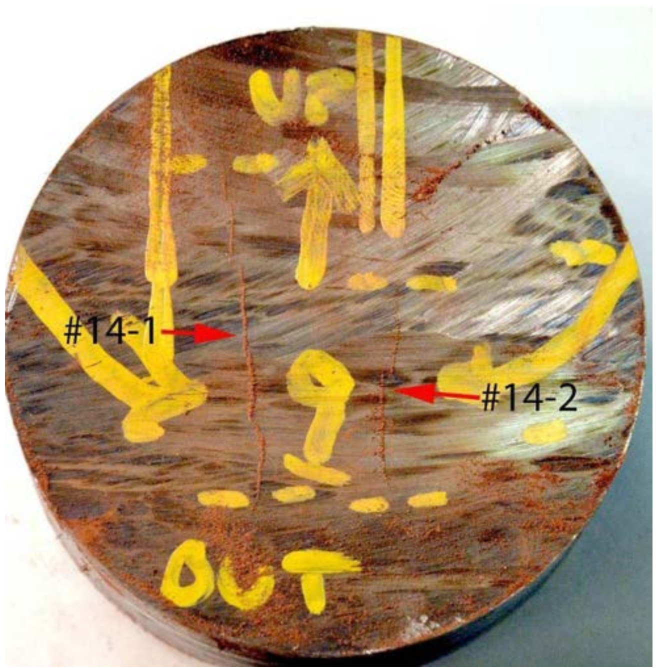


Figure 14 Surface cracks in core of tie chord butt-weld highlighted by magnetic particle testing (Jendrzejewski, J, Hills, J. and Hopwood, T., “Metallurgical Evaluation of Flaw Indications in Tie Chord Transition Butt Welds from the I-64 Sherman Minton Bridge,” New York Bridge Conference, 2014)

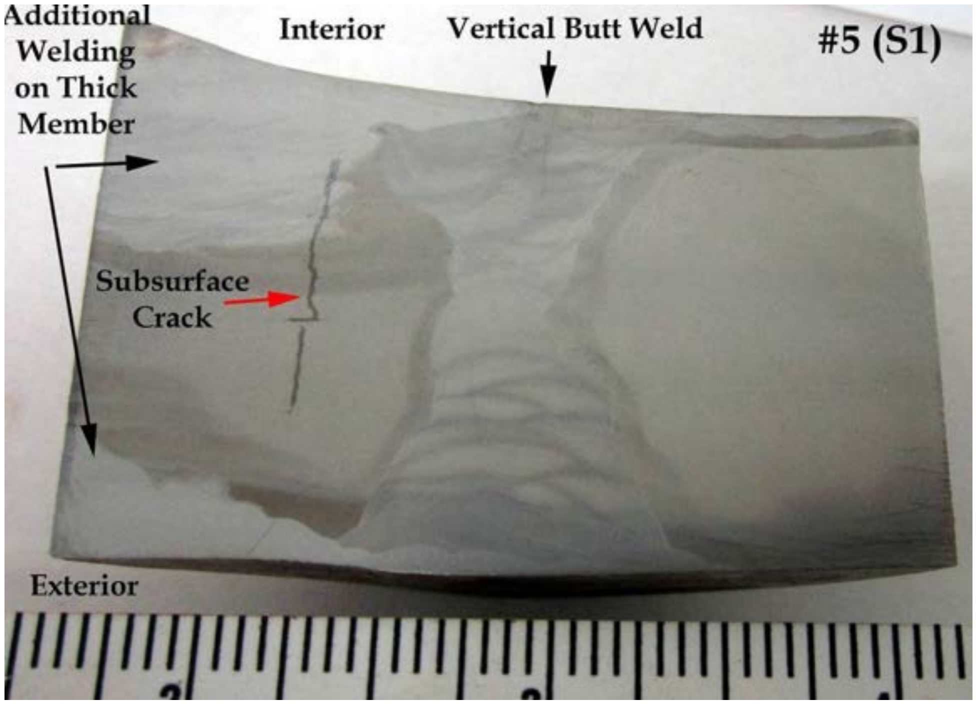


Figure 15 Internal crack in tie chord butt-weld (Jendrzejewski, J, Hills, J. and Hopwood, T., "Metallurgical Evaluation of Flaw Indications in Tie Chord Transition Butt Welds from the I-64 Sherman Minton Bridge," New York Bridge Conference, 2014)

2.2 Nondestructive Evaluation Methods

NDE methods are intended to detect and characterize flaws in materials (e.g., steel), providing an indication to the test operator that identifies locations where there is a change in condition compared to the bulk of the material. The operator must interpret that indication and determine whether it is a flaw, the type of flaw (if possible) and whether that flaw constitutes a defect. The latter judgement may lie outside the expertise and authority of the test operator.

Common NDE methods are typically classified as external (surface) methods and internal (subsurface) methods. Some methods can detect flaws both on and beneath the surface. Magnetic particle testing can detect external and near-surface internal flaws. Ultrasonic testing can be used to detect some surface breaking flaws. There are many NDE options available for use on bridges. However, six NDE methods have typically identified for use on common steel bridge inspection tasks. These are:

- Penetrant testing (PT)
- Magnetic particle testing (MT)
- Eddy current testing (ET)
- Radiographic testing (RT)
- Ultrasonic testing (UT)
- Acoustic emission testing (AET)

PT, MT and ET are typically considered external/surface test methods. RT and UT are considered internal tests. AET is used for flaw presence and location based upon flaw dynamic activity (e.g., crack growth). That flaw activity can also be considered a measure of flaw severity.

2.2.1 External/Surface NDE Methods

External/surface NDE methods are typically the simplest to apply and easiest to interpret. The steel plates or rolled shapes used on steel bridges are of limited thicknesses and, when growing cracks occur in them, they usually are superficial or break the surface at some point. Those may be benign or sub-critical while undergoing stable growth by fatigue or corrosion cracking. Slow growth usually permits their timely detection using external/surface NDE methods prior to component failure. The most common method is probably PT, followed by MT and then ET. Notable characteristics of those tests are described below.

2.2.1.1 Dye Penetrant Testing

- Uses
  - PT is used to find surface-breaking cracks and other flaws.
- Equipment/materials
  - Dye penetrants for bridge use are typically supplied in kits that contain the necessary chemicals in three aerosol spray cans, each for a specific step in the test process (a cleaner, a penetrant and a developer). Fluorescent dyes require the use of special black lights. Wire brushes (hand or powered) /grinding discs, hammers and scrapers are useful for surface preparation along with rags for cleaning and testing. Chemical paint removers may be used if the test area is properly cleaned.
- Surface preparation
  - Paint and foreign materials must be removed from the test area. The initial cleaning usually requires initial mechanical surface preparation to strip off paint and built up surface grime and rust. A cleaner is then applied to dissolve any remaining dirt or surface films.
- Principle of operation/procedure
  - After the surface is cleaned and wiped, a penetrant is sprayed over the test surface. It contains a colored pigment (e.g., red) in a thin oil that lets it to flow into surface defects by capillary action. After a holding period during which penetrant works into cracks and other flaws, excess penetrant is wiped from the test surface until none is visible. Thereafter, the developer is applied as a thin spray-on film, which deposits a white powdery layer over the test area. The developer extracts penetrant residing in cracks and other flaws, providing a colored indication of the presence of those flaws against the white background of the developer. After waiting for the developer to interact with the penetrant, the test surface is visually inspected with the contrasting colored indication highlighting the presence, length and width of the flaw (Figures 16, 17). In addition to the use of visible dyes, kits are available that use fluorescent penetrants. The application process is the same as for dye penetrants. After the developer is applied, a black light is used, which causes the penetrant to fluoresce, providing high contrast especially in areas of poor lighting. This method would work well where nighttime testing is performed or in sheltered (enclosed) areas.
- Detection/interpretation/recording
  - Generally interpreting what type of flaw is present is relatively straightforward. Cracks show up as visible linear continuous or intermittent indications. The inspector records the presence of the flaw by taking a picture and noting its dimensions and location on the bridge component.
- Bridge applications/limitations
  - This method is simple and inexpensive and can provide initial detection of flaws and confirmation of visual inspections. It can be readily used by bridge inspectors. It is slow and may not be cost effective if more than two or three locations need to be evaluated. Like visual inspection, it cannot detect subsurface flaws or evaluate the depth of surface-breaking flaws. The method is not as effective for irregular surface finishes and roughness.

Visible dye may not work well in areas of poor lighting, and fluorescent dye may not work when exposed to ambient light during daytime.

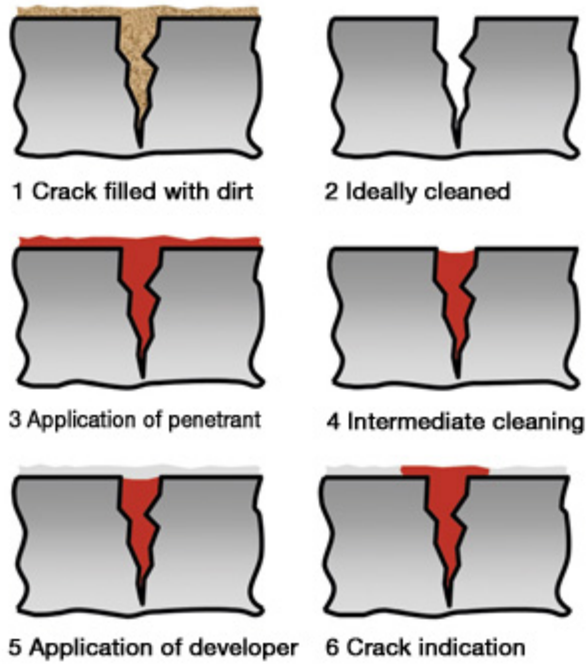


Figure 16 Steps in performing a dye penetrant test (Karl Deutsch, http://www.karldeutsch.de/KD_GENERAL_KnowledgeBase_PT_EN_M1.html)

Figure 17 Dye penetrant test on cracked area on faulty weld repair of upper chord member

2.2.1.2 Magnetic Particle Testing

- Uses

- MT can be used to detect exterior/surface and near-surface internal flaws in steel (and iron) bridge components. It requires less careful surface preparation than dye penetrant testing and, overall, is faster to apply.

- Equipment/materials
  - Necessary test equipment includes permanent magnets or battery/AC powered yokes. Visible or fluorescent magnetic (iron) particles are required along with a bulb applicator (dry method) or aerosol cans of powder suspension (wet method) and pie gage (recommended). A black light with fluorescent particles is required. Wire brushes (hand or powered) /grinding discs, hammers, scrapers and rags are useful for surface preparation. Chemical paint removers may be used.
- Surface preparation
  - The test area should be clean, dry and free of contaminants. Some surface preparation is required to remove surface contaminants such as oil, grease, rust, thick paint and weld spatter. MT can be used over paint with a coating thickness of up to 2 mils. Since nearly all bridge coatings are 3-4 times that thickness, the best practice is to remove bridge coatings down to bare metal/mill scale.
- Principle of operation/procedure
  - Permanent magnets and yokes (when powered) create magnetic fields in steel bridge components between the poles of magnets or poles created by the legs of a yoke. This generates lines of magnetic flux running between magnets or the legs of a yoke. Any flaw that cuts across those lines of flux will create a localized area of flux leakage. The flaw will not support as great a magnetic field as the surrounding steel, which causes the magnetic field to spread out and apparently leak out of the test piece. The greatest amount of flux leakage occurs when the flaw is perpendicular to the lines of flux with an orientation of 45^{o} considered the minimum for reliable generation of an indication (Figure 18). That requires proper alignment of the magnets/yoke legs relative to anticipated location of a flaw if it is suspected to be relatively linear and straight. For dry MT, a dusting of iron powder/filings is applied to the test area. With the magnetic force still applied, the surface is lightly blown to remove excess iron particles. In response, particles are attracted to and cluster at magnetic leakage (flaw) sites, forming a visible indication (Figure 19). For wet MT on bridges, iron particles in a suspension of water or oil are typically sprayed from an aerosol cans onto test areas. Immediately after the spray out, the test area is magnetized using a yoke and then inspected.

Figure 18 Use of AC yoke for magnetic particle inspection of web-to-flange fillet weld on tie-chord. The yoke is aligned to detect a crack in the toe of a longitudinal web-to-flange fillet weld on the tie chord

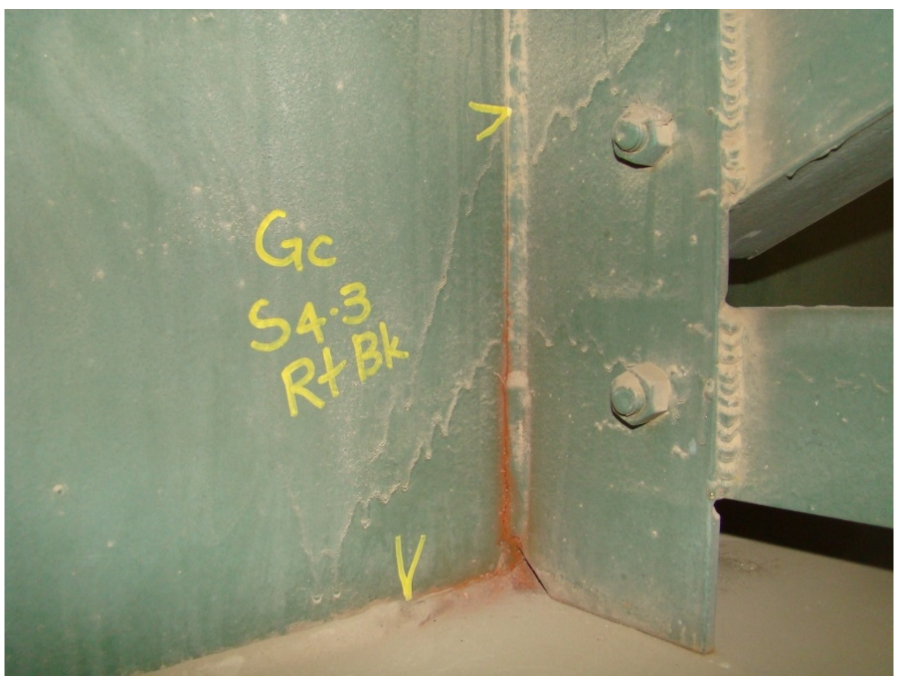


Figure 19 Magnetic particle indication of surface-breaking cracks

- Detection/interpretation/recoding
    - Most commercial powders have various pigments, typically gray or red, to highlight resulting visible indications. For both the dry and wet magnetic particle test methods, visible and fluorescent magnetic particles are available. Sometimes a white coating is applied to the surface prior to conducting visible particle tests (dry or wet) to enhance contrast and improve detection. Benefits and limitations of both types of

particles/indications are similar to those for visible and fluorescent dye penetrants. The inspector can record the presence of the flaw by taking a picture and noting its dimensions and location on the bridge component. They can also cover the indication with clear tape and extract from the test area for a hardcopy record.

- Bridge applications/limitations
    - This method is relatively simple and requires a minimum of operator training. Thus it is ideal for use by bridge inspectors. AC yokes are suitable for identifying exterior/surface flaws. DC yokes can test for exterior/surface and internal/near-surface flaws. MT is generally considered a poor choice for internal flaw detection, and the method is typically reserved for exterior/surface flaws. The method can have problems with irregular surface finishes and roughness (Figure 20). This method is more cost-effective than dye penetrant testing as it can be performed quicker. However, its use probably needs to be limited to testing a few sites, especially where lane closures are required for access to test sites. Problems have been observed with incorrectly using magnetic particle testing over thick paint. Operators typically do not test the strength/orientation of the magnetic field when using magnetic particle testing.

Figure 20 Possible MT crack indicated on in fillet weld subsequently evaluated by UT

2.2.1.3 Eddy Current Testing

- Uses
    - ET can be used to detect exterior/surface and near-surface internal flaws in steel (and iron) bridge components.
- Equipment/materials
    - Unlike PT and MT, ET does not use consumable materials. It employs a portable battery powered ET flaw detector (with electronic signal generator, controls, signal sensor circuitry and an impedance-plane screen), lead wires and probes along with reference standards for coatings and crack depth. It is a more advanced NDE method than PT or MT and requires operator training and experience. For testing typical structural steel, a weld probe is

recommended along with a paint probe (to assess coating thickness and compensate calibration using shims) and a test block with 2, 1 and 0.5 mm notches. Wire brushes (hand or powered), grinding discs, hammers, scrapers and rags are useful for surface preparation.

- Surface preparation
  - Minimum surface preparation is required (possibly removal of stratified rust, weld spatter or heavy deposits of debris/pigeon droppings). ET can be performed over paint films up to 80 mils thick.
- Principle of operation/procedure
  - The ET flaw detector creates AC current in the probe containing a wound wire coil (the primary coil). When the probe is placed on the test piece, the current creates a dynamic magnetic field about the probe that will create circular eddy currents in a test piece centered on the probe. In steel, the penetration of eddy currents into the material are very limited, and the testing has a *skin effect* that limits the ability of eddy current testing to surface and near-surface flaws. Flaws transverse to the circular movement of the eddy currents disturb the induced magnetic field and impact the current flow in the probe, which provides a means for detection in flaw detector electronics (Figure 21). Flaws aligned closer to parallel with the eddy currents provide reduced flaw indications. Care must be taken when testing close to edges of plates due to disturbances in the eddy current field (edge effects) that prevent flaw detection. For flaw location, an ET flaw detector — an eddy scope — is used, which contains an impedance plane screen on the test unit that lets operator to view the effect of the imposed magnetic field of the probe interacting with the induced field in the test piece. The screen displays the interacting inductive reactance of the coupled probe-test piece versus resistance generated by the couple. When the probe moves over the test piece and detects a surface or near-surface flaw, the magnetic field induced by the probe changes. That change is shown by movement of a normally centered pip on the screen that deflects (Figure 22). If a conventional single-wound coil probe is lifted off the test piece, the signal would change due to the *lift-off* effect. Specialized weld probes are available that minimize lift-off effects. These do not require the removal of paint or tight rust, and can be used to inspect irregular surfaces such as those found on code-acceptable fillet welds. The length of the flaw detected is normally considered as equivalent to the diameter of probe's coil. It is sensitive to small surface flaws (e.g., cracks down to 0.20" in length). The test provides flaw indications in real time.

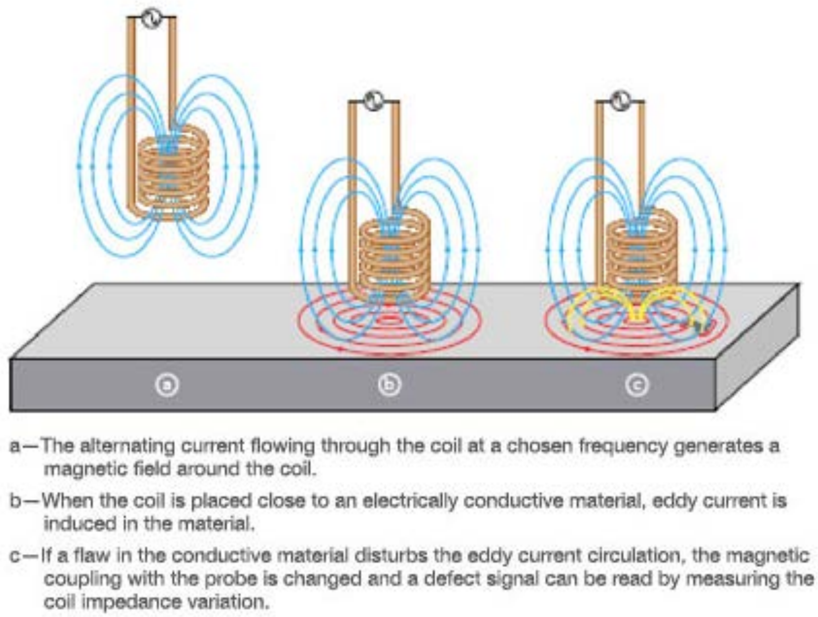


Figure 21 Operating principle of eddy current testing (picture courtesy of Olympus®

Figure 22 Eddy current unit showing pip deflection due to crack indication (picture courtesy of Nortec®

- Detection/interpretation/recording
  - Operators must be skilled in selecting the appropriate probe and instrument settings and in manipulating the probe over the test piece. They should also have knowledge needed to determine whether screen indications are from legitimate flaws rather than from geometric effects. The probe is typically moved in a zig-zag pattern along the heat-affected zone next to the weld and over the weld bead. It then makes a linear sweep along the weld toes (7).

Indications are traces of vertical movements of the pip as the probe is manipulated over a flaw in the test piece. Crack depths can be determined by comparing the signal deflection of cracks with known depths to reference standards. Crack lengths are determined by moving the probe along the crack until a specified drop of peak signal is obtained. Most advanced eddy current units are digital and have a storage function to record screen traces and provide test reports. This method is the most cost-effective for performing multiple tests on a structure.

- Bridge applications/limitations
    - The surface preparation is minimal, the testing is rapid and the test data can be captured and digitally uploaded for economic reporting. ET is faster than PT and MT, and can be used where multiple inspection sites are present on a bridge, especially where disruptive lane closures are required (8). It can also be used for inspections with rope access. Proper equipment selection and set-up is necessary, requiring a skilled operator. Tests can be affected by surface roughness and variations in test piece material properties. This is an emerging NDE method for bridge applications.

2.3 Internal/Subsurface NDE Methods

Internal/subsurface NDE methods are used to characterize and size indications that have been previously detected by visual inspections or external/surface NDE methods. They are also used where cracks have been detected to provide accurate subsurface sizing for fracture assessments and repairs. They can also be used to investigate test sites where concerns exist about the integrity of components with limited access (e.g., pins), questionable welds/weld repairs or impact damage. These methods are slow and require costly equipment as well as trained, experienced operators. The two primary methods used for bridge steel, radiography and conventional ultrasonic testing have different capabilities and can be used as complimentary tests to confirm findings from the other method.

2.3.1 Radiographic Testing

- Uses
    - RT can be used to detect subsurface volumetric flaws such a porosity and slag inclusions. If properly oriented, it can detect planar flaws including cracks, lack of penetration and lack of fusion.
- Equipment/materials
    - In the field, RT requires a radiation source (x-ray tube or isotope/case), film cassettes (consumables) or digital flat panel detector, penetrameters and film markers. Wire brushes (hand or powered)/grinding discs and scrapers and rags may be necessary for coating removal. Post-test facilities and equipment are required to develop film or download images for viewing.
- Principle of operation/procedure
- RT detects flaws in steel and steel welds by examining differences in the absorption of shortwave radiation, x-rays or gamma waves that penetrate steel. When properly exposed, unflawed steel will absorb most of the radiation. On one side of the test piece (bridge component), a radiation source is placed, an x-ray tube for x-rays or a radioactive metal isotope (such as cobalt 60 or iridium 192) for gamma rays. For most bridge inspections, iridium 192 has been the primary source used in bridge radiography. To apply it in the field, a small capsule of the isotope is mounted in a protective container (projector). The projector is fairly heavy as it uses a dense metal (e.g., lead) to protect the operator (radiographer) from radiation continuously emitted from the isotope. The radiographer locates the projector on a firm support away from the test location (Figure 23). He attaches a guide tube to an opening on one end of the projector and a control cable on the other end. The control cable is used to extend the radiographic source, a pellet of iridium 192, from the projector through the guide tube by cranking a reel assembly that extends and retracts the control cable. There is an

opening (snout) at the end of the guide tube that is directed towards the test location on the steel component (Figure 24). Exposure begins once the radiographer extends the source to the snout. On the opposite side of the test piece is a medium for detecting radiation that penetrates through the steel. Typically, RT employs a type of film that is exposed by the radiation (Figure 25). The film is housed in a cassette to prevent its exposure to light and handling damage. A small image quality indicator is positioned on the radiation source side of the test piece. The indicator (a penetrameter) may be a metal strip that contains small holes of different sizes, notches, or a nonmetallic cassette which contains wires of varying diameters. It is used to confirm image quality and sensitivity of the film to spot defects (usually set at a 2% absorbance of the thickness of the test piece). Lead letters, numbers and arrows (markers) are used to identify/locate the image (Figure 26). Prior to taking the radiograph, the operator marks the test area and carefully locates the film on the face of the test piece on the opposite side of the radiographic source, and then places markers on the source side. Once the proper exposure duration has been reached, the guide cable is retracted and the radiographic source is withdrawn from the guide tube into the projector. The film cassette is removed from the test piece and taken to a dark room where the film is extracted and developed. Developed film provides an image of the test piece along with differences in exposure due to variations in steel thickness in the test piece and the presence of any flaws that allow more radiation to pass through the test piece than intact steel. A newer method termed digital radiography uses flat panels of sensors similar in concept to those used in digital cameras. The panel is located like the film and receives radiation that passes through the test piece from the source. The radiation charges the small sensors on the flat panel. The exposed panel is taken to a laboratory where a device reads the panel and produces an image just like the conventional film but view on a computer screen (Figure 27). Advantages of digital radiography include not requiring a development step and production of a digital image that can be manipulated and applied directly to a report.

Figure 23 RT Projector (Arrow) mounted on H beam. Note yellow guide tube running from camera to location under the beam

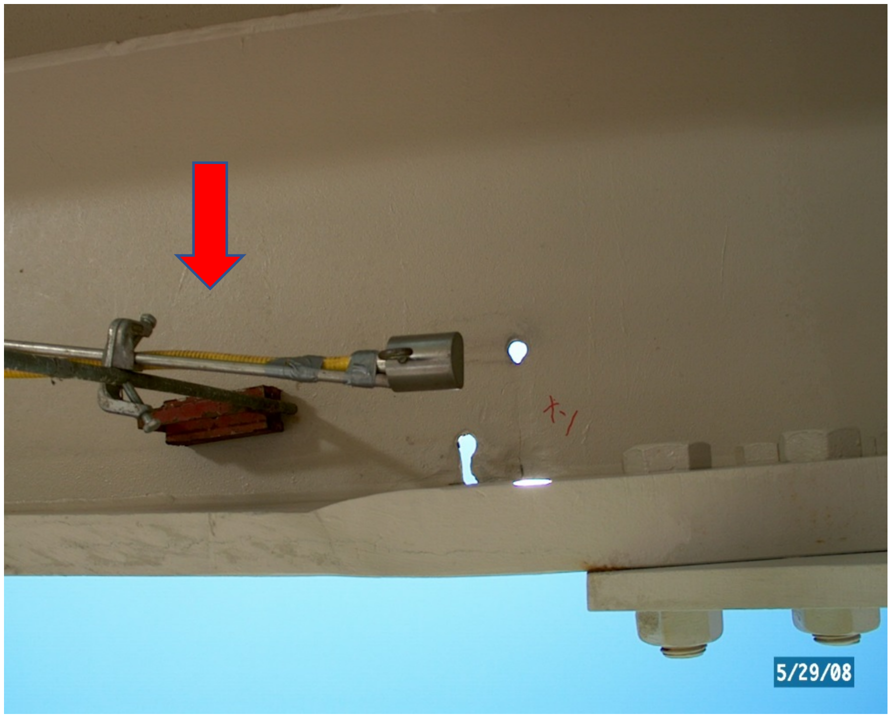


Figure 24 Upward view showing RT guide tube and collimator aimed at 5-1/16” crack in H-beam web for radiograph from underside of flaw (arrow)

Figure 25 RT film pack mounted on outer face of inboard flange for radiograph of flange-to-web fillet weld and flange at 5-1/16” crack terminus

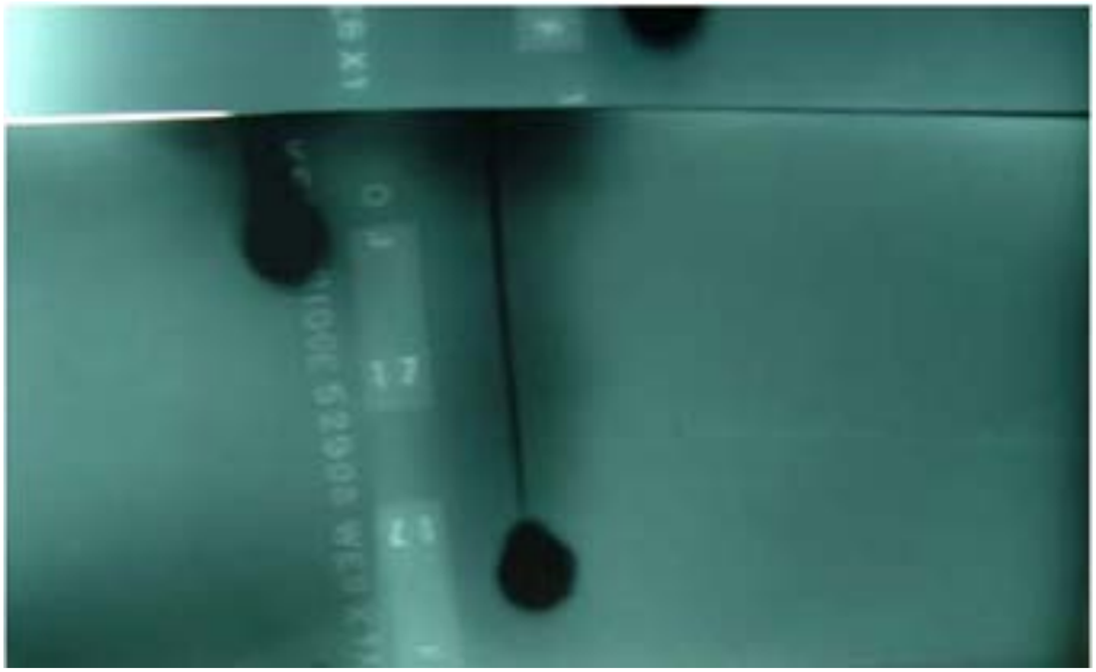


Figure 26 Radiographic film showing crack from improper repair. Note lead identification and penetrameters adjacent to flaw

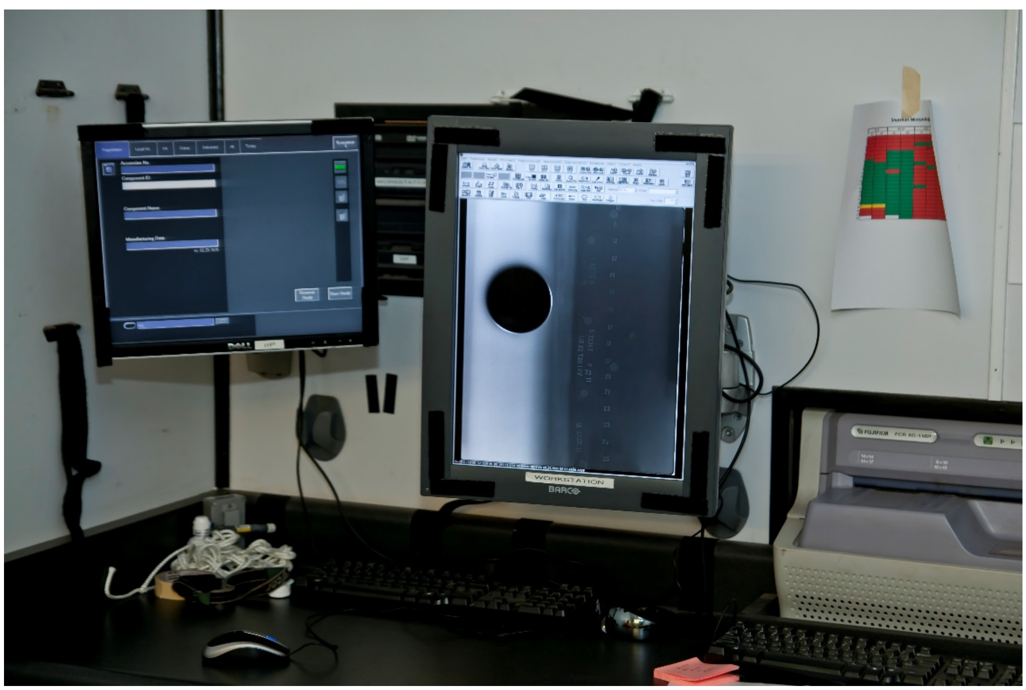


Figure 27 Digital radiography used for bridge weld inspection (previously cored butt-weld shown on screen)

- Detection/interpretation/recording
  - The film locations should be marked on the test piece for future reference/actions. The developed film/downloaded digital image is placed on a viewer and inspected by a technician proficient in interpreting industrial radiographic images. The technician interprets the images and relates visual discontinuities to specific flaws, if they are present,

(flaw characterization) and sizes the flaw. Usually, a combination of flaw size and type are used to determine flaw criticality (if a flaw is considered a defect).

- Bridge applications/limitations
    - There is a radiation hazard attendant with RT that requires care in its use. Test areas need to be cordoned off and placarded to prevent entry by non-test personnel. Film development/digital image downloading entails a post-processing step that creates a delay between testing and evaluation. For a few images, those media are typically taken from the field to a shop for post-processing. When a large number of field tests/images are required, a portable laboratory can be taken to the field for developing and evaluating of both conventional and digital radiographs. Weld evaluations may require multiple shots to detect planar flaws at a single test location. Existing lead paint may inhibit RT, necessitating coating removal. Irregular weld surfaces may need to be smoothed by grinding to provide suitable contrast between flaws and intact steel. The test provides a good record (picture) of indications and dependable interpretations of the types of flaws detected. Its use can assist in proper decision making regarding the need/extent of any repairs. The visual images can be easily reported and stored for future evaluations. While good for detecting volumetric indications, RT cannot detect planar defects unless the x-ray source is properly aligned. As such, it cannot be used to detect rolling laminations in steel plates. For internal/ subsurface flaws, RT locates them in relation to the placement of the film/flat panel detector on the surface of the test piece, but it cannot provide their depth. This is probably the most expensive NDE method to use on bridges in the field. However, it may eliminate the need to remove/replace bridge paint (a significant expense), and it can be used to verify other NDE methods. In some cases, it offers critical information about flaw severity and the need for follow-up remedial work.

2.3.2 Ultrasonic Testing

- Uses
    - UT can be used to detect subsurface volumetric flaws such a cluster porosity and slag inclusions. It is the best internal subsurface NDE method for detecting planar flaws including cracks, lack of penetration, lack of fusion and laminations. It can be used to detect material thickness for corrosion measurements and construction errors. It can also be used to detect surface-breaking flaws (e.g., cracks). UT has been used to determine if ends of stay cable strands have cracked at the anchor blocks.
- Equipment/materials
    - Portable UT flaw detectors incorporate pulser-receiver, electronic signal controls and display screen, lead wires, transducers, reference gages and couplant (a consumable). For thickness measurement, a portable ultrasonic thickness gage incorporates pulser-receiver, electronic signal controls and digital thickness display, lead wires, transducers and couplant. Wire brushes (hand or powered) /grinding discs, hammers, scrapers and rags are useful for surface preparation. Chemical paint removers may be used.
- Principle of operation/procedures
    - UT flaw detectors generate electronic pulses at specific amplitudes and frequencies through lead wires connected to piezoelectric crystals in probes (transducers). The electronic pulses cause the piezoelectric crystals to vibrate as specific frequencies converting the electric pulse to high frequency mechanical pulses (typically 2-5 MHz for steel). The transducers are coupled to the steel test piece using a viscous fluid (e.g., a thick oil). Depending on the transducer type, the mechanical pulses generate compression or shear waves in the atomic structure (crystalline) of the steel. Compression waves consist of alternating layers of steel atoms that compress or expand due to the elastic motion imparted by the transducer. Shear waves consist of particles that oscillate at right angles to the direction of wave motion.

Transducers generating compression waves are called straight beam transducers while those generating shear waves are called angle beam transducers. Angle beam transducers can also be designed to produce shallow surface waves that travel along the surface of the test piece. The pulser-receiver circuitry in the flaw detector uses the transducers to generate mechanical sound in the test piece and receive reflections from test surface (near field), any intervening discontinuities and the test-piece back wall for straight beam tests appear on the display screen (Figure 28). For calibrated pulse-echo UT, the test device/transducer is calibrated using a standard reference block (Figure 29). Special references can be used for problematic test environments (Figure 30). Adjustments in signal power and pulse reception are used to display the entry pulse of the wave (near field) and back wall and the time delay on the display screen grid. In the A-scan mode on the display screen, the vertical axis is set for a calibrated system amplification and horizontal axis is set for distance (along the beam path) using a reference block. To perform ultrasonic testing, the test area should be clean of paint, debris (including rust), slag and weld spatter, and relatively smooth.

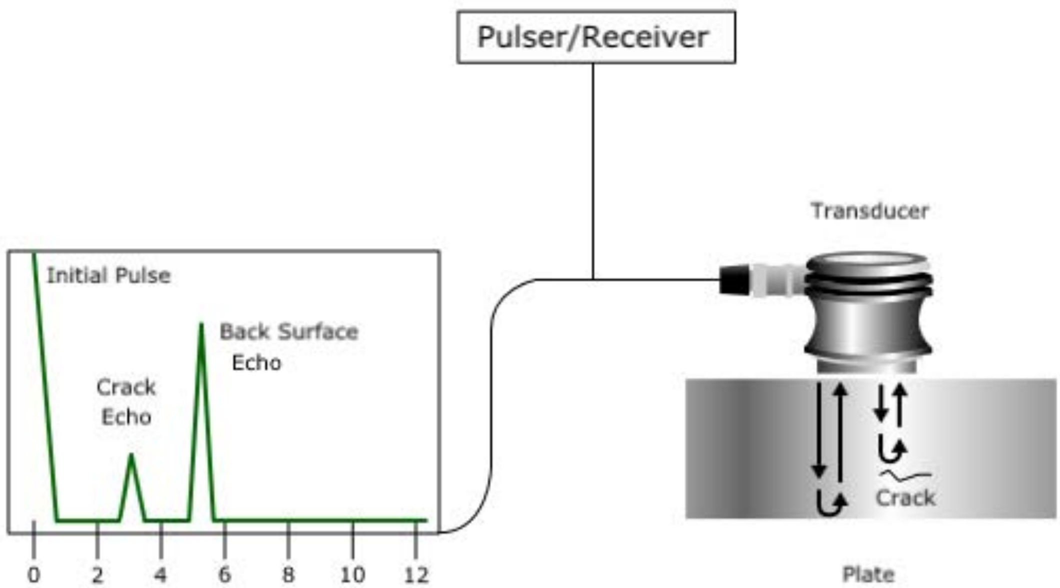


Figure 28 Straight beam UT showing detection of crack with transverse orientation to the sound wave (Image provided by the NDT Resource Center at Iowa State University)

Figure 29 Calibration of shear wave UT using a standard IIW reference block

Figure 30 Special UT calibration plate made for inspection of bolted splice plates

Straight beam scanning entails spreading a couplant over the test surface. Then a straight beam transducer is manually moved over the surface of the test piece (either entirely or in a grid pattern). The display screen exhibits the test in profile (A-scan) with reflector amplitudes on the x-axis and distance along the wave beam indicated on the y-axis. Intervening indications, shown as vertical peaks between the near field and back wall reflections on the display screen may warrant further investigations (nondestructive or invasive, such as coring). Straight beam testing can detect flaws oriented parallel to the surface of the test piece, such as internal planar laminations in steel plate that cannot be detected by other NDE methods. A typical use in the inspection of bridge anchor bolts and pins (Figures 31, 32). However, it may not be effective for flaws perpendicular to the test surface, as is the case with most cracks. Straight beam scanning is typically done prior to shear wave testing to detect laminations that would interfere with the latter test (Figures 33, 34).

Figure 31 Straight beam UT of uplift bearing anchor bolt

Figure 32 Typical ultrasonic pin inspection (Indiana Statewide Pin And Hanger Inspection Program – Final Report Indiana Route 237 over Ohio River Cannelton, Indiana, Bridge No. 237-62-06512 A, Prepared for the Indiana Department of Transportation by Wiss, Janney, Elstner Associates, Inc., November 15, 2000)

Figure 33 Straight beam UT testing of weld area prior to shear wave testing

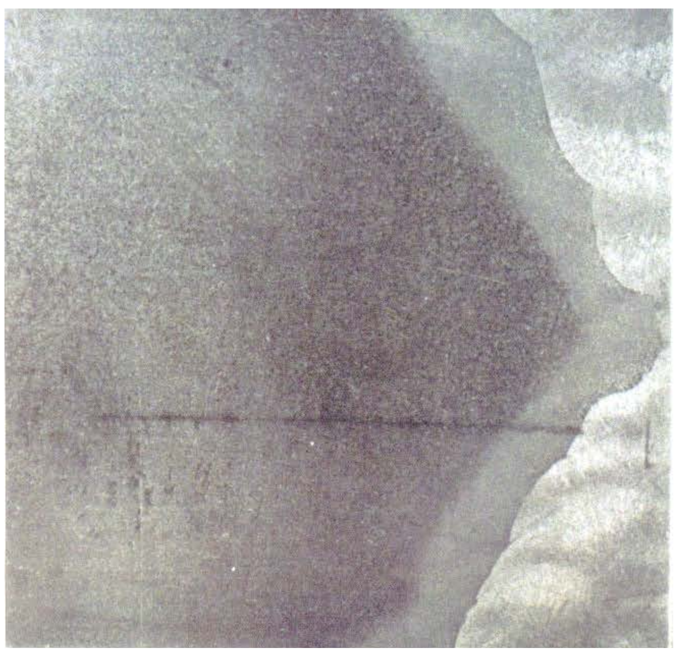


Figure 34 Lamination in steel plate adjacent to weld making shear wave UT impractical for NDE

- **Shear wave testing** is performed using an angle-beam probe that consists of a straight beam transducer and a plastic wedge to induce shear waves at a refracted angle into the test piece (Figure 35). It is usually employed to inspect welds for flaws (Figures 36-39). The angled sound path reflects the sound beam from the back wall to improve the detection of flaws in and around welded areas by orienting the beams nearly perpendicular to subsurface weld flaws.

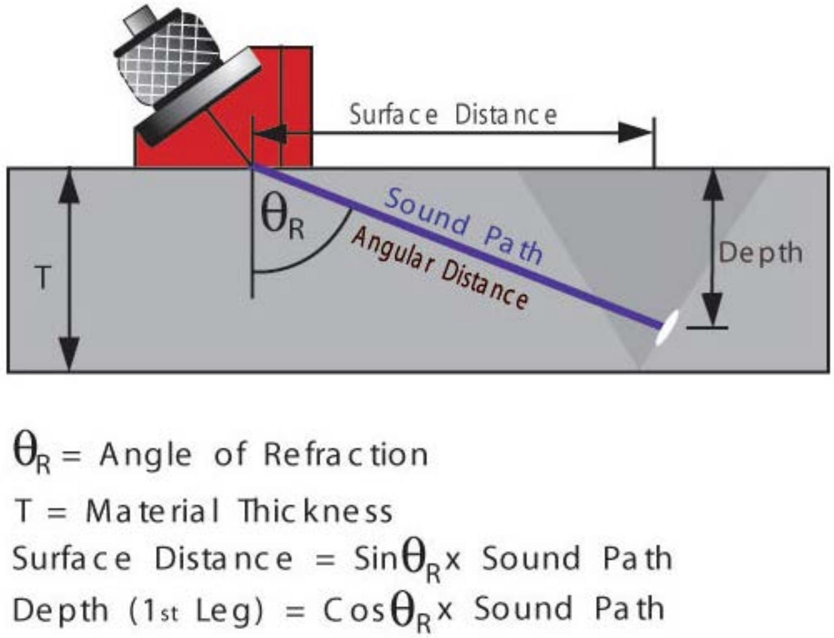


Figure 35 Shear wave (angle beam) UT testing of a weld show first leg detection of a flaw (Image provided by the NDT Resource Center at Iowa State University)

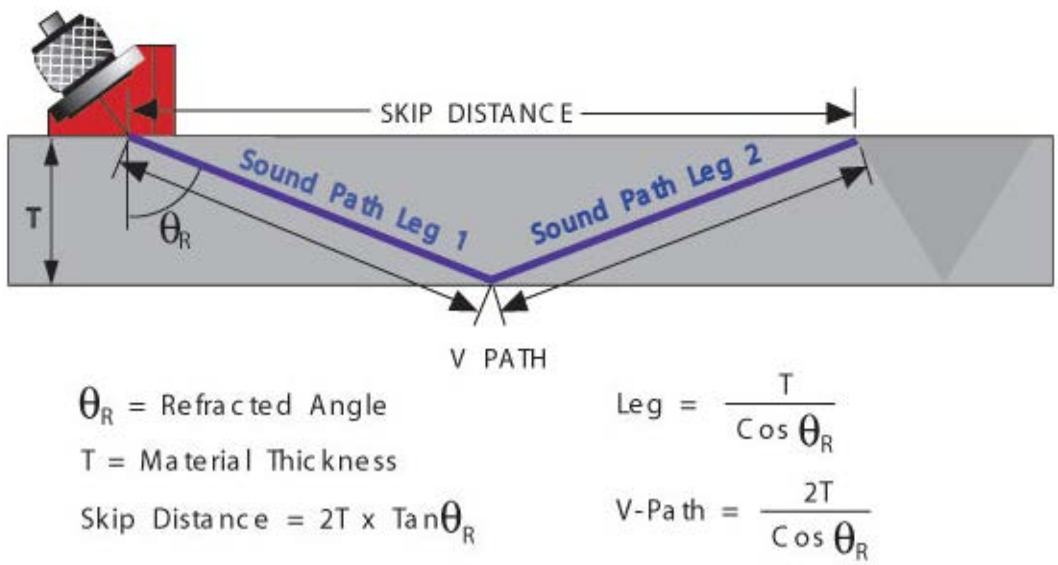


Figure 36 Shear wave (angle beam) UT testing of a weld show second leg reflected off the back wall of test piece (Image provided by the NDT Resource Center at Iowa State University)

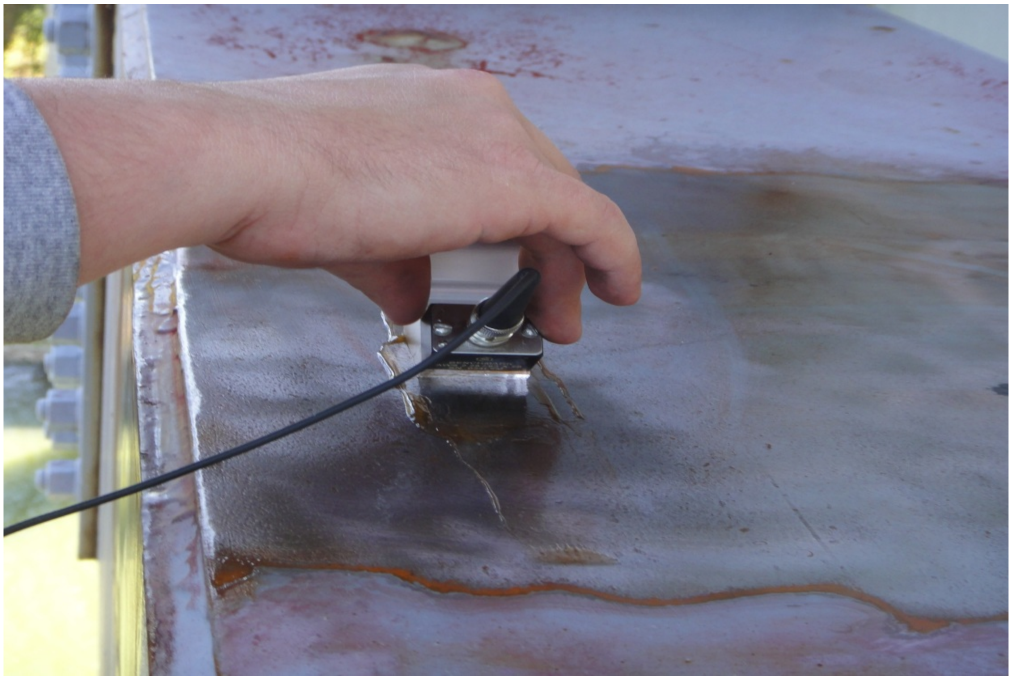


Figure 37 Shear wave UT of a butt-weld using an angle-beam transducer on I-275 Carroll Cropper Bridge

Figure 38 UT display screen showing A-scan image of a flaw detected during shear wave testing

Figure 39 NDE operator inspecting a weld where MT indicated a potential crack (Reference Figure 20)

When viewing the display screen, the operator sees the entry pulse. Any flaws encountered are indicated as vertical peaks on the display screen and are related to the magnitude of the reflected wave. The shear wave beam generated by the transducer travels at a refracted angle (usually 45^{o} to 70^{o} from a line normal to the test piece surface). For shear wave testing, the operator manipulates the transducer in a raster pattern at pre-determined distances from desired inspection locations (e.g., weld lines) to scan for potential flaws. Any flaws of sufficient size will provide distinct reflections (vertical peaks) along the beam sound path (i.e. the x-axis of the display screen). Once a significant discontinuity is located, the operator performs flaw evaluation by manipulating the transducer/pulse at the indication to receive the maximum amplitude reflection. Its length is then determined using a predefined procedure (e.g. AWS 6 dB drop). The transducer's position is typically marked on the test piece along with the location/depth of the flaw. For reporting purposes, most new UT flaw detectors store screen images and other data for subsequent reporting. For both straight beam and shear wave testing, flaw detection is the best choice when the beams are normal to the maximum profile of the flaws. It is least effective when the beams are parallel to them, especially planar flaws.

- Two other UT units are of note, thickness gages and phased-array flaw detectors.
- UT thickness gages employ dual element transducers with two piezoelectric crystals housed in a single transducer. One of the crystals is used to generate an ultrasonic longitudinal wave like a conventional straight beam transducer and the other one receives the reflected pulse and converts it to an electric signal. The unit measures the elapsed time between pulse generation and receipt of the reflection. Based on the speed of sound of a longitudinal wave in steel, the thickness of the test piece is calculated and displayed as a numeric output on a digital screen. Conventional UT flaw detectors can also be used to perform this inspection when equipped with dual element transducers. These devices can be used to measure section loss in steel components such as gusset plates (Figure 40).

Figure 40 Use of ultrasonic thickness gage to inspect a gusset plate (Weir, W.R., "Methodology in Gusset Plate Inspection, Evaluation & Rating," Transystems Presentation at the Midwest Bridge Working Group Fall Meeting, December 10, 2008).

- **Phased array ultrasonic flaw detectors** perform an advanced form of ultrasonic imaging termed phased array ultrasonic testing (PAUT). The method employs sensors that contain many small electronic transducers in arrays (e.g., a row) that are pulsed sequentially to establish a pattern of constructive wave interference that results in a beam at a set angle. Changing the timing of the pulsing generates waves at a number of angles, allowing a sensor to sweep a test area (e.g., a weld) without manipulating it, as is the case with conventional shear wave testing. Special PAUT-capable UT flaw detectors are required to perform this type of testing. Using a PAUT flaw detector, the sensor can be moved transversely (parallel to the weld line) and sweep the weld with ultrasound, providing a rapid test compared to conventional shear wave UT. An encoder is used to digitally record the lateral location of the probe as it is moved along the weld line for subsequently locating any flaws that are encountered. Test data are stored digitally in the flaw detector and can be subsequently viewed in conventional A and B scan modes as well as the sector (S scan) mode. Other probes are available that enable PAUT to detect corrosion damage (loss-of-section).
- Detection/interpretation/recording
    - For straight beam and shear wave testing, the amplitudes of reflections between the sound entry (near field) and back wall are related to flaws. The amplitudes of the reflection indicate the flaw's severity. These amplitudes (as shown on the y-axis of the display screen) are related to flaw size and distance along the sound path between the transducer and the flaw and is reflected in the attenuation of the initial and reflected pulses. For both test methods, the flaw detector is calibrated for distance and sensitivity using a reference standard (e.g., for shear wave testing the AWS Shear Wave Distance/Sensitivity Calibration Block). Newer digital UT flaw detectors have on-screen distance-amplitude correction and/or AWS reflector indication ratings to assist the operator in evaluating flaw severity. PAUT testing provides better imaging and image processing resulting in better, quicker characterization and sizing of flaws. PAUT allows the operator to access more UT information from the weld and easily locate any flaws based upon depth of the test piece and surface distance between the flaw and the transducer. The method is better at

characterizing flaws than conventional shear wave testing. It can also be used for corrosion mapping if one face of a component is intact.

- Bridge applications/limitations
  - Ultrasonic testing incorporates a range of test devices/methods to address a range of inspection requirements for steel bridges. It can be used to confirm surface indications, inspect plate structures for cracks or corrosion damage, detect cracking in structural members (including pins and fittings), and inspect strands for cracking (Figure 41). It can accurately locate crack tips prior to placing check holes (Figure 42). The testing is generally faster than radiography, but overall may be more time consuming for coating removal/replacement. Preliminary mapping of steel plates and rolled shape with straight beams may indicate that shear wave UT or PAUT will not be effective for NDE due to the presence of laminations that block the sound path. This would be more likely for steel components that were shop inspected by radiography rather than ultrasonic testing. Some UT tests (e.g., shear wave testing) require that operators have significant knowledge and skills to perform the test correctly and interpret the results. PAUT is an emerging technology that offers several benefits over conventional UT methods, but it has not been widely used to date to confirm its potential. Previous research demonstrated that PAUT identifies fabrication shop defects as accurately as RT or UT, and showed potential (in the shop) for reducing inspection costs (9).

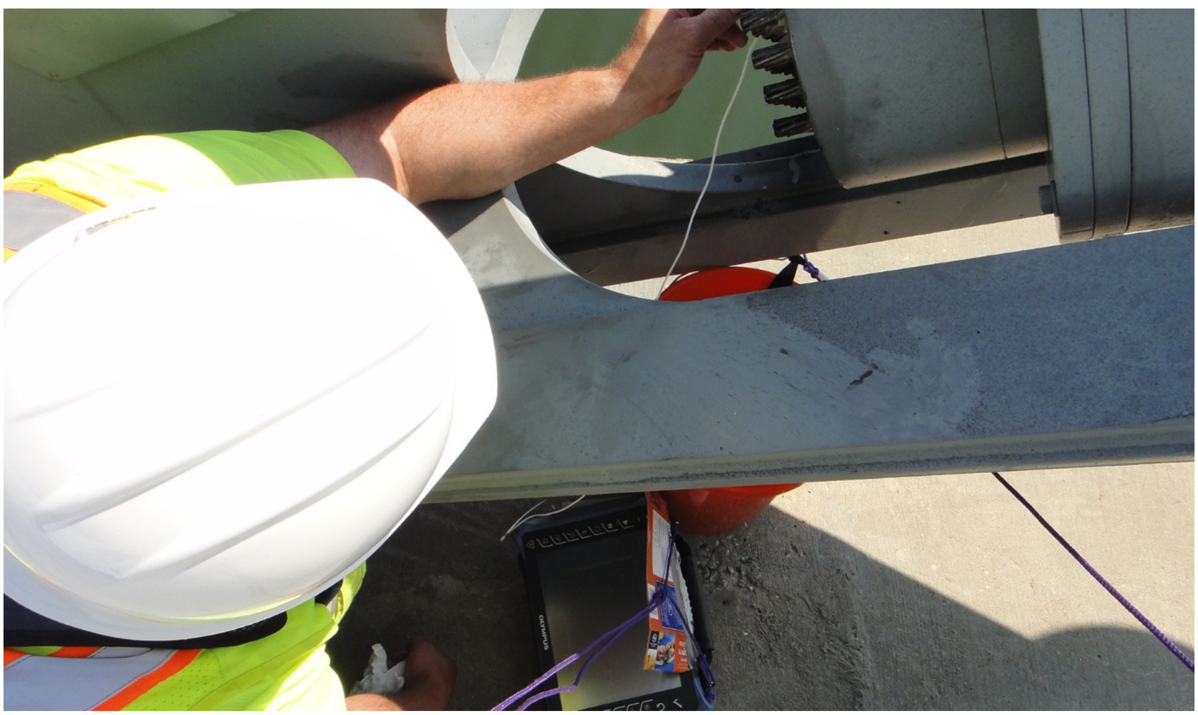


Figure 41 UT operator inspecting wires at deck anchorages of a cable stayed bridge for potential cracking

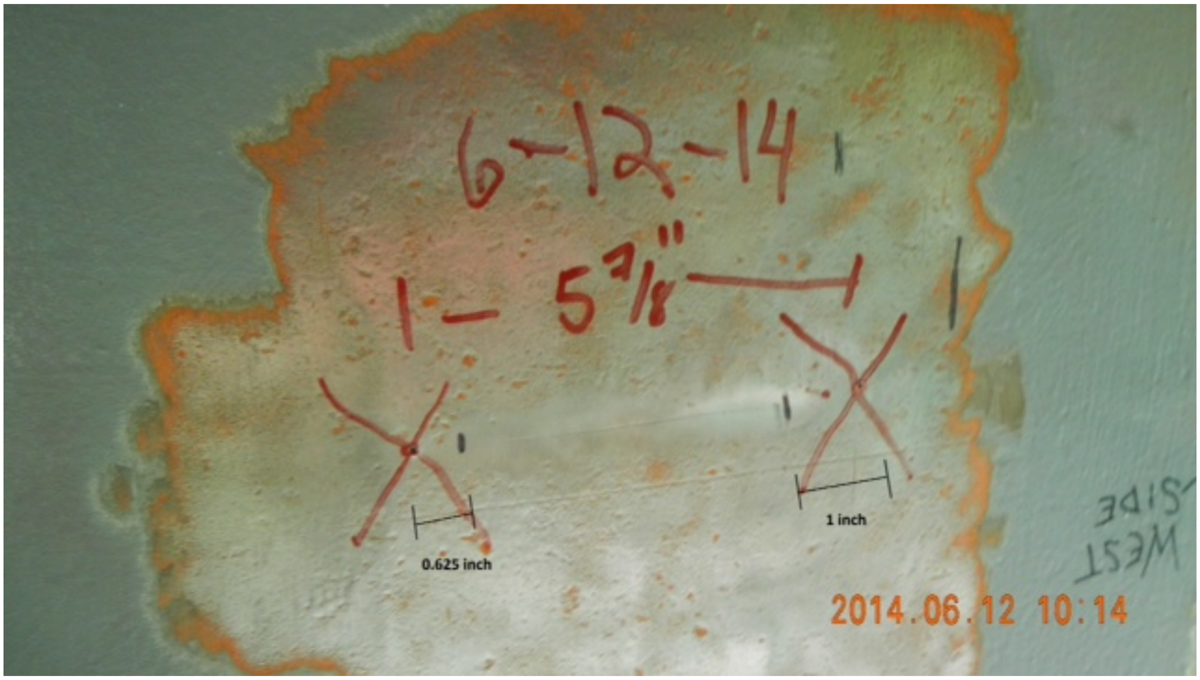


Figure 42 Crack tip locations-surface-breaking (visible) indicated by black dots and subsurface indicated by red X-marks

2.3.3 Acoustic Emission Testing

- Uses
    - AET is used to detect activity in known cracks that would indicate sub-critical crack growth due to fatigue, stress corrosion or corrosion cracking. It can detect nucleating/growing cracks in circumstances where they are not readily accessible or observable due to their small size. It can locate welding flaws both in-process and during cooling.
- Equipment/materials
    - AET involves the following equipment: multiple-channel AE monitor with parallel signal measurement channels, PC (typically), signal processing software, lead cables, pre-amplifiers, transducers, magnetic hold-down fixtures, mechanical pencils or ultrasonic pulsers, measuring tape, carpenters square and couplant. Wire brushes (hand or powered) /grinding discs, hammers, scrapers and rags are useful for surface preparation.
- Principle of operation/procedure
    - AET is used to monitor materials undergoing dynamic processes (e.g., structural loading, weld heating and cooling and corrosion). Steel undergoing one or more of these processes releases elastic energy that can be detected in a manner similar to what is done to monitor earthquakes (it has been termed micro-seismic testing). The amount of energy released by materials during most processes is usually small and must be greatly amplified to be heard (Figure 43).

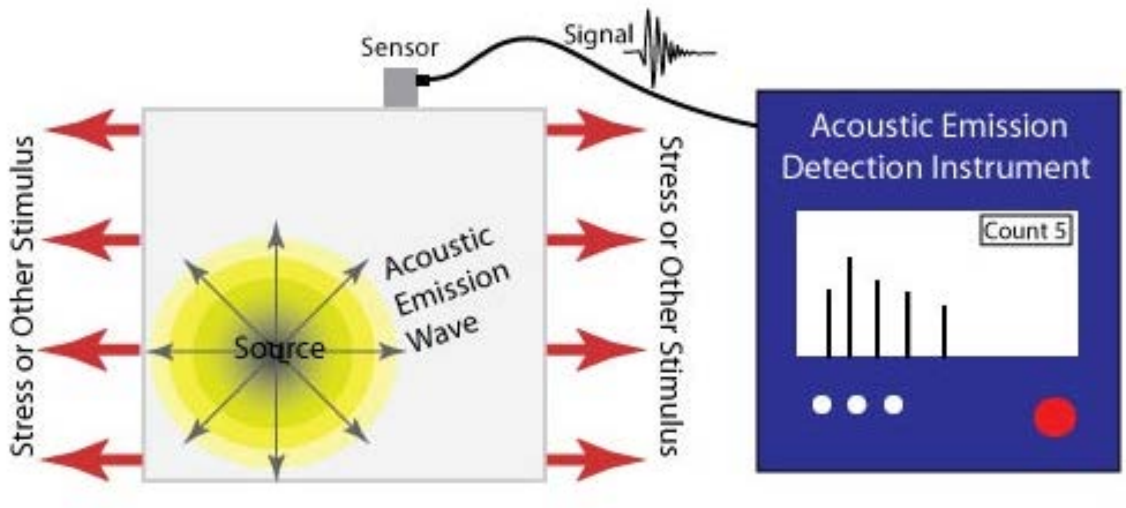


Figure 43 Schematic of AE generation and detection by an AE monitor (Image provided by the NDT Resource Center at Iowa State University)

Audible monitoring is impractical for most structures, and the current AET is performed at ultrasonic frequencies to avoid interference from background noise. Sources of acoustic emissions in steel are typically localized plasticity at a crack tip, corrosion product fretting in cracks, and fracturing of nonmetallic impurities in areas of high localized stresses. Sources of extraneous noises on bridges that mimic acoustic emissions include rubbing of fasteners or faying plates, movement of loose deck joints, electric noise from vehicles and power lines, and fretting between deck concrete and steel beams. The number of noise events on a bridge may exceed those from valid sources by several thousand to one. AE monitoring systems use a number of techniques to reject noise and characterize/locate only valid acoustic emissions from sources of interest.

Acoustic emissions from cracks are generated as elastic waves in steel components that are radiated outward in a circular pattern from the vicinity of crack tips, which are point sources. AE events are transient, typically occurring for only a few micro-seconds. Sensitive listening sensors, transducers similar to those used for ultrasonic testing, generate electronic signals when vibrated by the waves in the steel's surface. They typically operate in ultrasonic frequencies > 100 kHz. The transducers are acoustically coupled to the steel using a viscous fluid. On steel bridges, the paint needs to be removed at the attachment sites prior to installing the transducers. Magnetic hold-downs are typically used to maintain the transducer attachment/coupling to a test piece. The transducers operate at ultrasonic frequencies greater than 20,000 Hz and are immune to audible noise. They produce weak electric signals. Pre-amplifiers connected to the transducers by short lead wires increase the signal strength. They send the magnified signals through longer signal cables to an AE monitoring device that contains clocking, signal conditioning/processing and digital storage circuitry. It contains multiple channel inputs from external transducers on a common time base. Some AE monitors can accept simultaneous signal inputs from other devices such as strain gage conditioners. An AE monitor may have an integrated microprocessor, controls and data displays, or be controlled or send output data to an external PC. The AE monitor/PC system uses software that controls the test run, sets internal test parameters and processes the resulting data that is generated by the transducer signals.

AE systems for monitoring structures such as bridges typically require multiple transducers, which are placed on a test piece in geometric arrays to locate cracks and preclude interference/false signals from noise sources. Where a visible/known/suspected flaw is located, a single active transducer may be placed in the immediate vicinity (point location). It can be surrounded at a distance by several *guard* transducers (Figure 44). With this layout, only signals that first strike the active transducer are considered. Other transducer arrays are used to locate flaws along a line (e.g., to monitor a weld line) using a linear array, or to locate flaws in a pre-defined area using a planar array. A linear array uses two transducers at a known spacing to monitor flaw activity that occurs on the line connecting them. Once a transducer is struck by a qualifying AE wave, a clock in the AE monitor measures how long it takes for the second transducer to be struck. If that time is less than the time required for sound to travel the distance between the two transducers, it is considered a valid signal and its location along the line is based upon the time gap between receipts of the transducer signals. Planar transducer arrays are used infrequently on bridges. They consist of transducers arranged in geometric patterns of known transducer spacing on the surface of a test piece using three or more transducers. They measure the arrival times of valid AE signals from each transducer and indicate flaw locations using the same triangulation methods used by geophones to locate earthquakes. In high-noise backgrounds, linear and planar arrays may require additional *guard* transducers to prevent spurious wave activity from providing false results. Clocking and algorithms in the AE monitoring logic/signal processing circuitry are used to locate valid AE activity and reject noise.

Figure 44 Battery powered AE device (in protective container) with transducer array used to monitor butt weld

The processing circuitry/AE monitoring logic can further evaluate the signals to ensure they are from valid sources and categorize the severity of a flaw based upon the energy and frequency of occurrence of valid AE signals. In modern AE systems, data for a test run are recorded and typically analyzed and reported electronically from the host PC. Significant knowledge is required to evaluate a test piece and determine the proper transducer layout and equipment settings. The transducer array is precisely located and spaced on a structural member. A mechanical pencil is typically used to break leads that simulate AE activity and can be used to check the location function of the AE monitor/software/transducer array. An ultrasonic pulser can also be used for this purpose. It may remain in place during the test period and be automatically energized to test the array's function over time. AET can be performed in real time or during monitoring (either continuous or for a specific duration).

Bridge AET requires structural loading. Some AE sources are very active and can provide suitable indications in a short monitoring period (a few hours) if normal traffic is used to promote AE activity. A knowledgeable AE operator (or their supervisor) is required to design the test array and equipment requirements, test parameters, structural loading method and test duration. For short-term testing, the equipment can be stored near the test site and powered by a generator. For remote locations, battery powered AE monitors can be used for short test intervals (several hours). For longer tests, weatherproof equipment enclosures may be required, along with hard wiring to available electric power or a solar power source, to permit continuous long-term AE monitoring.

- Detection/interpretation/recording
  - AE test procedures are driven by anticipated defect/location. AE activity is generated as discrete events termed AE *hits* when measured by electronic signals from transducers. Valid AE activity signals are characterized by the time of receipt of the signal (to each transducer), which are converted into source locations by PC software and various signal parameters that relate to the type of source and frequency and magnitude of its intensity (energy release). Some AE systems are capable of near-real time display of location, signal activity (frequency and magnitude) and even categorization data (e.g., determination that the data is crack related). With AE systems capable of multi-parametric inputs, AE activity can be recorded and potentially displayed concurrently on a computer monitor, which enables the correlations of AE events with heavy loading/strains in bridge components under test.

AE activity can be generated by normal traffic, where the test duration generally depends on traffic volumes/weights outside the control of the operator. Proof loads in trucks can be run over a bridge, causing growing flaws to produce AE activity (Figure 45). Where longer test periods or continuous monitoring is employed, the data can be coupled to alarms notifying the operator of valid AE activity or it can be post-processed after test runs/intervals are completed. Post-processing may be required for short test runs if the AE equipment is not capable of near-real-time data processing. The operator will typically use software supplied by the AE monitor manufacturer to evaluate the stored AE data after downloading it to a PC. The operator will review the signal parameters including frequency and magnitude of AE events and clustering of AE *hits* at locations along linear or planar arrays. Based upon that review, the operator can determine whether an AE source (e.g. crack) is active and, if strain gage data are available, the stresses/strains in a structural component necessary to drive AE activity. As the data are stored digitally and commonly processed using standard AE software, reporting is usually simplified even for complex analyses.

Figure 45 Heavy proof-type loads being run over a bridge for strain testing and AE monitoring of weld cracks

- Bridge applications/limitations
  - AET can provide valuable results that can be used to validate follow-up decisions about bridge flaws (real or suspected). It can be used to evaluate many test requirements posed by steel bridges including plates, rolled shapes, pins and cable fittings and wires. It can monitor existing cracks or suspect locations, such as questionable weld repairs, and determine if there is potential for nucleating/growing cracks. It can evaluate retrofits (Figures 46, 47) to rapidly determine if they effectively arrest crack growth (10). It can be used to monitor problem locations where cracking can lead to structural component failure and frequent application of conventional NDE methods is impractical (e.g., eyebars) or impossible (e.g., stay cables). It does not geometrically define flaws though it can locate them in relation to a transducer array. Conventional NDE methods may be required to effect repairs of flaws detected by AE testing. In some applications, it can be susceptible to false calls where the noise-rejection features of the test layout and equipment are defeated. An expert operator can minimize those occurrences.

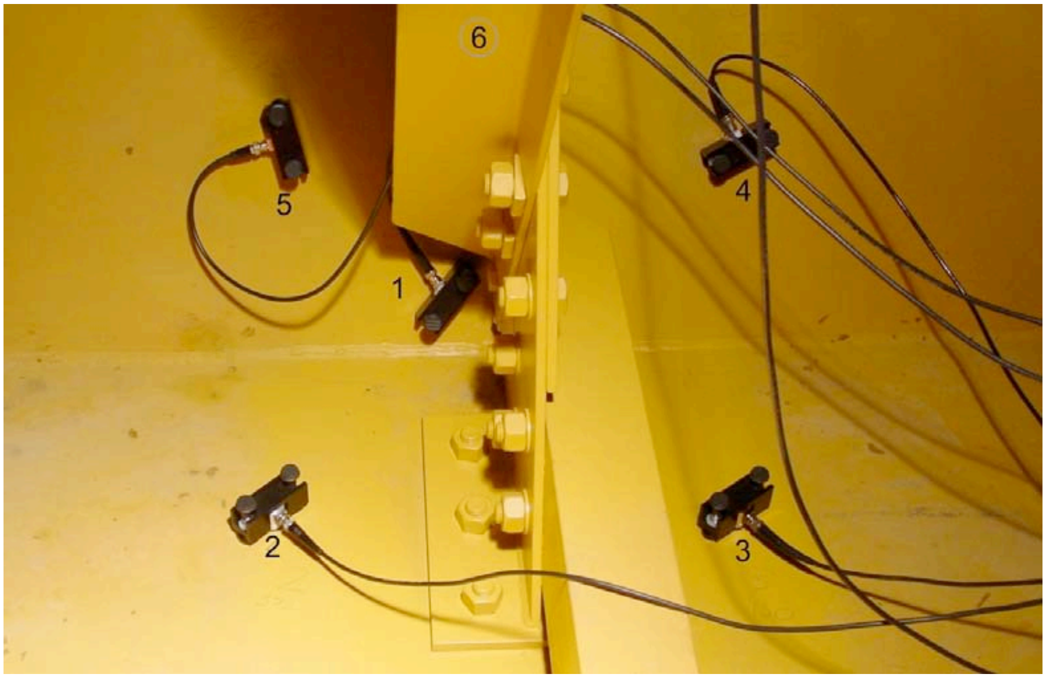


Figure 46 AE transducer array used to evaluate a bridge retrofit (.Kosnik, D.E. and Marron, D.R., "Acoustic Emission Evaluation of Retrofits on the I-80 Bryte Bend Bridge Sacramento, CA, Infrastructure Technology Institute, Northwestern University, Acoustic Emission Working Group, Advances in Acoustic Emission – 2007)

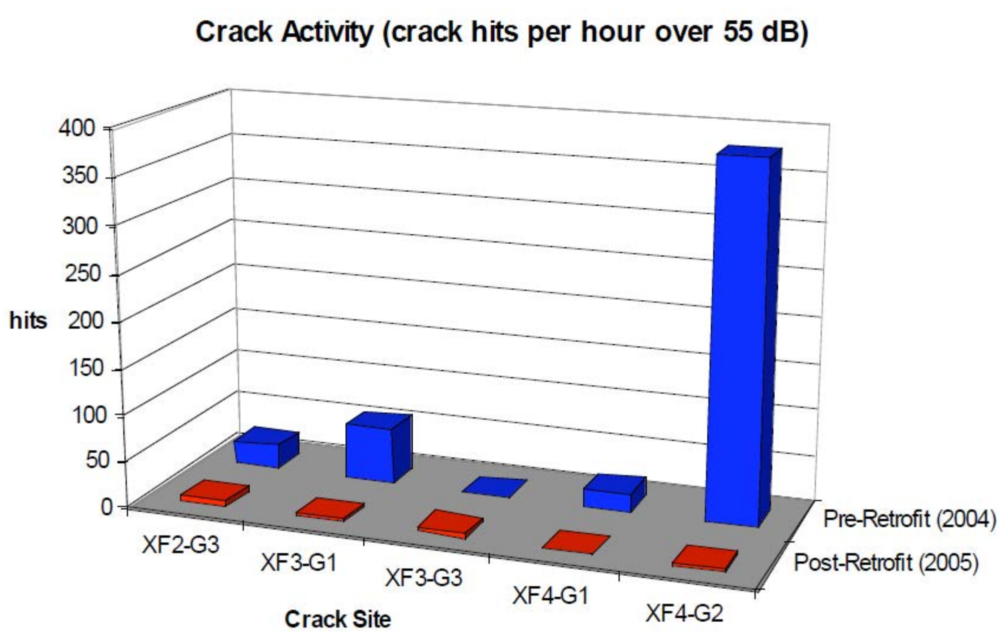


Figure 47 Crack AE activity before and after retrofit (Kosnik, D.E. and Marron, D.R., "Acoustic Emission Evaluation of Retrofits on the I-80 Bryte Bend Bridge Sacramento, CA, Infrastructure Technology Institute, Northwestern University, Acoustic Emission Working Group, Advances in Acoustic Emission – 2007)

2.4 Miscellaneous NDE Methods

There are a variety of nondestructive methods that can and have been used in the field on bridges. Hardness tests (ultrasonic, rebound and impact) have been used to determine whether the proper steel has been selected for a structural component. Magnetic flux leakage testing has been used to detect flaws in stay cables (Figure 48). Electrochemical crack growth detection is used like AET to assess surface-breaking cracks for fatigue (Metal Fatigue Solutions™). Simple sounding has been used to detect broken rivets in built-up beams by hitting the rivet heads and monitoring the resulting sound. Crack propagation gages can be placed to detect crack growth in structural health monitoring (SHM) applications (Figure 49). Irregular corrosion loss on gusset plates and other structural members can be detected using 3D scanning.

Figure 48 Magnetic flux testing of a stay cable on the I-310 Hale Boggs Bridge near Luling, Louisiana

Figure 49 Crack gage mounted on bridge floorbeam

2.5 Ancillary Test Tools and Supplies

When performing field NDE testing, especially tests that require visual confirmation (i.e., PT and MT), good lighting is important even where subdued lighting is present. Bridge inspectors performing those tests should carry flash lights and 10x magnifiers to supplement visual inspections.

Indelible ink markers are suitable for identifying flaw locations for pictures and follow-up repairs. If a test location is directly exposed to the weather and the marking needs last several years, paint pens should be used. Crack tips should be marked and dated to determine if they have grown during later inspections. Magnetic rulers can be placed next to flaws for scaling when pictures are taken. Crack tips can be marked with a punch to provide a more permanent indication. Pocket knives or multi-tools are useful for locally scraping off paint/rust or probing a surface flaw.

Right-angle grinders equipped with wire brushes, non-woven (3M™) pads or grinding discs may be used for local coating removal (required for some NDE tests). Minor paint removal may be acceptable in sheltered areas of a bridge not exposed to deck runoff (i.e., under joints). Where extensive paint removal has occurred in preparation for NDE operations or where bridge steel is directly exposed to the elements, disturbed locations should be repainted. Wiping surfaces with solvents is recommended prior to repainting to remove any oily contamination and dust (especially when dye penetrants are used). A direct-to-metal acrylic paint is recommended for spot coating repairs due to its user friendliness and fast drying time. Those can be applied by brushing or rolling. Care should be taken to apply the coating to a dry surface and, if possible, during the middle of the day. Rain should not be in the forecast during the 24 hours following application. A tooth gage can be used to ensure that the proper coating thickness has been achieved.

Irregular surfaces may need to be flattened or smoothed to permit NDE testing or visual evaluations. Right angle grinders with abrasive discs can be used for flat work. For more complex surfaces (e.g., fillet welds) die grinders with carbide bits are recommended.

2.6 Surface Preparation, Worker Safety and Compliance with Environmental Regulations

In addition to working at heights, the primary working hazards facing bridge inspectors and NDE personnel relate to coating removal. Coating removal poses several safety issues for KYTC bridge inspectors and consultants tasked with removing coatings. Chief among these is the removal of old lead-based paints. Any orange or red primers should be suspected of containing lead. Some older paint top coats can contain as much lead as the red lead primers. LeadCheck™ swabs facilitate rapid identification of lead paint.

Hand or power tools create airborne dust particles that require respiratory protection. Eye protection should be used with power tools. When using liquid dye penetrants, some sources recommend avoiding coating removal by mechanic means and the use of paint strippers. Paint strippers effective on structural coatings typically contain dangerous solvents (e.g., methylene chloride) or harsh chemicals (e.g., caustics) that require respiratory, eye and skin protection. Those chemicals usually require some time to react with the existing coating and may create a residue that may be considered hazardous or toxic. Lead paint residue from liquid paint stripping may be a hazardous waste.

Lead paint and mill scale on older bridges can be removed using special vacuum-equipped shrouded hand tools (sand paper or paint stripping pads). This requires that workers wear protective clothing, have respirators on hand, and receive training on the hazards posed by lead (lead awareness training) and how to safely remove lead. Lead paint that has been removed should be captured and disposed of properly (Figure 50). An on-site wash facility and disposal bags should be provided to ensure worker hygiene and to discard disposable coveralls. For large projects on-site temporary storage may be required if lead paint is removed. KYTC's Division of Environmental Analysis can assist with that task. On a large-scale inspection project involving removal of lead paint, it may be useful to employ a paint contractor for both paint removal prior to NDE work and subsequent repainting.

There are many useful overview documents (e.g., reports or websites) that provide information in addition to what this report contains (11-13). Readers should review this material to gain additional insight into the use of NDE for bridge inspections.

Figure 50 Technician removing lead-based painting using vacuum shrouded grinder with non-woven pad and wearing personal protection

3. Use of NDE for Bridge Inspections

3.1 Range of NDE Applications

NDE has a range of applications which, when properly considered prior to formulating and performing work, should factor into decisions about the NDE method(s) used, information sought, and potential outcomes. NDE can involve the evaluation of indications provided by other NDE methods, searching for potential flaws, flaw detection, flaw sizing, and flaw characterization.

3.1.1 Evaluations of Potential Flaw Indications

A key use of NDE is to evaluate indications (usually assumed to be cracks) detected by VT or another NDE method. If VT indicates a crack, it is usually evaluated using an external/surface NDE method (i.e., PT, MT or ET). If the indication is detected by one of the external/surface methods, it is typically evaluated using one of the internal/subsurface NDE methods (i.e., RT or UT — conventional or phased array). An indication detected by an internal/subsurface NDE method is usually evaluated by another internal/subsurface NDE method or coring/metallurgical analysis.

3.1.2 Searching for Potential Flaws

NDE can also be used to search for flaws in bridge locations where there are no prior indications of potential flaws. This type of application relates to a wide range of circumstances including:

1) improper weld repairs
2) fatigue-prone weld details
3) steel/weld concerns
4) where cracking has occurred in similar locations or on bridges with similar details
5) components that can't be inspected visually
6) suspect construction practices
7) corrosion damage
8) bridge members subjected to significant overloads
9) impact damage
10) evaluation of field welding or structural repairs/retrofits.

Periodically, improper weld repairs related to poor fabrication shop practices that were missed by shop QA inspections are encountered. Sometimes, field remediation actions are as problematic as improper repairs, especially if they are not well documented. In that case, several NDE methods may be used to substantiate the condition of the weld repair.

Fatigue-prone weld details can be evaluated to determine if cracking is occurring. Typically, fatigue cracks are present for about the last 10 percent of the stress cycles required for crack nucleation, growth, and final fracture. NDE can be applied in situations where there are significant concerns about structural integrity due to a variety of circumstances. This includes non-redundant bridges that have exceeded their safe-lives and may be at risk of failure, due to the cumulative damage caused by structural loading from traffic, wind and corrosion. Washer (14) described an ideal NDE methodology to detect cracks (Table 2).

Table 2 NDE System Requirements for Crack Detection in Steel Bridges — from Washer (14)

High speed/large coverage area	Sensitive through coatings
Real-time data analysis	Portability
Reliability	Indicated crack severity
Cognition	Unaffected by adverse environment

Some bridges may be at risk due to defective steels or problematic fabrication processes. One example is the US 18 Marquette-Joliet Bridge over the Mississippi River, which was built in 1975. Shortly thereafter, cracks were detected in the tie-chords. The cause was defective ASTM A441 steel (banding). Another example is the I-79 Neville Island Back Channel Bridge over the Ohio River near Pittsburgh, Pennsylvania that was closed a few months after its opening due to cracks in electroslag welds. One crack almost completely severed a deep girder and caused significant sags in the deck. Those welds had low toughness and were difficult to inspect using ultrasonic testing due to large grain sizes in the welds. The weld method is no longer used on bridges. No known bridges in Kentucky were fabricated using electroslag welding.

Several other Ohio River bridges owned by KYTC and other DOTs have experienced weld cracking of high yield strength quenched-and-tempered steels due to hydrogen cracking resulting from poor shop welding practices and spotty QA/QC NDE. In 2011, numerous weld cracks in the tie chord butt-welds of the I-64 Sherman Minton Bridge were identified. The Indiana DOT (INDOT) was concerned that one of these cracks could become an unstable fracture at colder temperatures. INDOT began an NDE project using UT to test a certain percentage of the butt-welds and upped the number tested after identifying additional flaws. Eventually, a major crack was discovered, which lead to closure of the bridge. At this point scope of the testing increased, adding RT and testing all weld locations. After this work had been completed, bridge tie chords were repaired. Fortunately, most of those bridges were constructed in the 1960s and early 1970s, and similar problems have not been encountered on major bridges constructed more recently.

NDE is often used to detect cracking at locations on a bridge or other bridges possessing similar details. In the early 1975, cracking was detected in tie-chord butt welds of the I-24 Bridge over the Ohio River near Paducah. The affected welds were eventually lapped with splice plates. Because of that problem, KYTC performed ultrasonic testing on all the tie-chord butt welds of the I-471 Dan Beard over the Ohio River at Newport. A location with major UT indication was cored, revealing the source of the UT indication to be a harmless lamination. UT was used to evaluate tie-chord butt welds of concern on the I-275 Carroll Cropper Bridge that contained ASTM A 514 steel (Reference Figure 37). During steel hardness testing on the Combs-Hehl twin bridges in 2008, inspectors found a cracked splice plate. As a consequence, an NDE consultant was contracted to perform UT on splice plates at similar locations in all four trusses of the two bridges to ensure that no other cracks were present.

3.1.3 Flaw Detection

Flaws are identified by NDE indications of various types. These can include visually observable surface flaws indicated by dye traces or magnetic particle lines, eddy current impedance plane scope traces, radiographic images, ultrasonic indications/thickness measurements and acoustic emission activity clusters. NDE operators are responsible for interpreting the indications as flaws in the steel bridge components. Generally, operators can make two types of errors — Type 1 errors, where the operator misses a flaw or does not properly interpret an indication as being related to a flaw, termed an *undercall*, and Type 2 errors where the operator misinterprets an anomalous indication as a flaw, termed an *overcall*. Elimination of Type 1 errors is based on choice of a proper NDE method and skill of the operator in apply it. Type 2 errors can be addressed by using a different operator or method to confirm or discount an initial NDE indication. An example of this is the use of UT to inspect an indication found using a surface method such as PT or MT. Flaw indications obtained by AET must be verified using a surface or internal NDE method.

3.1.4 Flaw Sizing

Once a flaw has been detected, it must be properly located and sized. If immediate repairs are not made, the flaw location must be recorded accurately to permit follow-up inspections or repairs. This process entails taking measurements and photographs, marking the bridge component and preparing a sketch showing the location, size, and orientation of a flaw. This information is reported and used to determine appropriate follow-up actions. Where fatigue is a concern, the tips of surface-breaking cracks can be marked with a punch or indelible ink pen (and the mark dated).

Generally, an internal NDE method (e.g. ultrasonic testing) provides the most accurate flaw sizing. When ultrasonic testing is used, there can be some variability in crack sizing among operators depending on their skill and technique. Prequalification procedures may limit those differences. Radiography may not be conservative when sizing tight cracks.

Accurate crack sizing is necessary if fracture mechanics methods are used to determine flaw criticality.

3.1.5 Flaw Characterization

NDE can be used to assess what types of flaws are present. Various methods have been used, including UT A-scan distance-reflector amplitude measurements. One reference grouped planar-type detects versus volumetric ones based on a distance-compensated amplitude rejection level based upon a specific calibration method (15).

Flaws vs. Defects — after detection, follow-up actions are required to determine the criticality of a flaw. An unacceptable flaw is considered a defect either when it falls outside of specifications or when it is anticipated that it would cause steel bridge components to fail in service. Besides flaw detection, NDE methods can be used for flaw sizing and activity (cracking). That information can be used in follow-up analyses to determine if the flaw is defective and warrants repair. In situations requiring immediate resolution, a range of NDE assets need to be used and supplementary information can guide actions such as coring, physical testing, and failure analysis.

Another factor to consider is the potential impact of a flaw on structure. This is addressed in terms of the nature of the flaw, the component where it is located and the potential impact of that component's fracture on structural integrity of the bridge. Cracks transverse to principal tensile stresses in fracture-critical members that are growing by fatigue are probably the most common critical circumstances encountered on steel bridges. Determining the criticality of a flaw can be a challenging task for bridge engineers especially when they are required to make quick decisions. The potential threat of a flaw to a bridge's structural integrity generally depends on its type, size, disposition in a structural component, type of steel involved, the impacted structural details and the magnitude and nature of the loading (both live and dead loads). Usually, flaw severity can be ranked from worst to least as cracks, lack of fusion, lack of penetration, arc strikes (welding), slag stringers and porosity (neglecting stress concentrators resulting from fabrication, corrosion or construction/service damage). Typically, the severity of non-crack flaws in steel bridges is related to their propensity to generate cracks in a fatigue environment. Characterization of flaws by type can be done readily for surface-breaking flaws (typically cracks). Subsurface flaws can be best characterized by type using radiography. It is generally easier to characterize flaw severity by size than by type. Ultrasonic testing has been used by KYTC to determine whether a surface indication detected by magnetic particle cracking is an actual crack.

Workmanship standards have been used by steel fabrication codes, such as the American Welding Society Bridge Welding Code D1.5. Flaws considered to be defects under those standards are generally conservative and in some cases, much smaller actual structures can be tolerated. The use of workmanship standards for evaluating flaws on in-service bridges is generally considered a conservative approach.

Another method of characterizing flaws, typically cracks, is to use fracture mechanics. Fracture mechanics relies on calculations to assess the severity of flaws. Typically, it takes the approximate form shown in Figure 51. When the combination of applied stress (σ), and crack length (α), reach a critical value, K_{IC}, a structural component can fail in an unstable manner. While fracture mechanics is widely applied in other sectors (e.g., pressure vessels, piping, aircraft), its use on bridges has been limited.

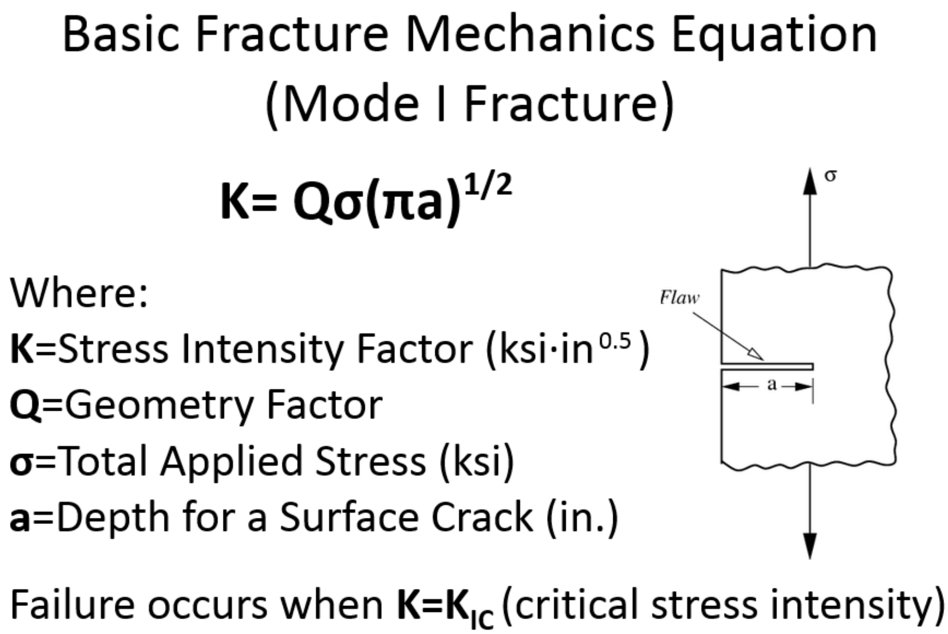


Figure 51 Fracture mechanics equation for edge crack

The Fracture Analysis Diagram (FAD) can be used to steel critical crack sizes when the service temperatures are below the nil-ductility temperature (NDT) where low-energy cleavage fractures occur (Figure 52). It provides stresses and associated critical crack sizes versus temperature relative to NDT. The lower bound is the Crack Arrest Test (CAT) curve, below which a crack will arrest itself rather than experience unstable growth. According to this theory, brittle fracture occurs below the NDT depending on crack size and stress. Above the NDT mixed-mode (elastic-plastic) fractures occur (up to the Fracture-Transition Line) requiring higher stresses to cause unstable fracture for a given crack size. A comparison of critical crack sizes in a high-strength steel based upon fracture mechanics and the FAD for various stress states are shown in Figure 53. In some cases, cracks significantly larger than those predicted by fracture mechanics to pose a threat of fracture have been found in bridge members (Figure 54).

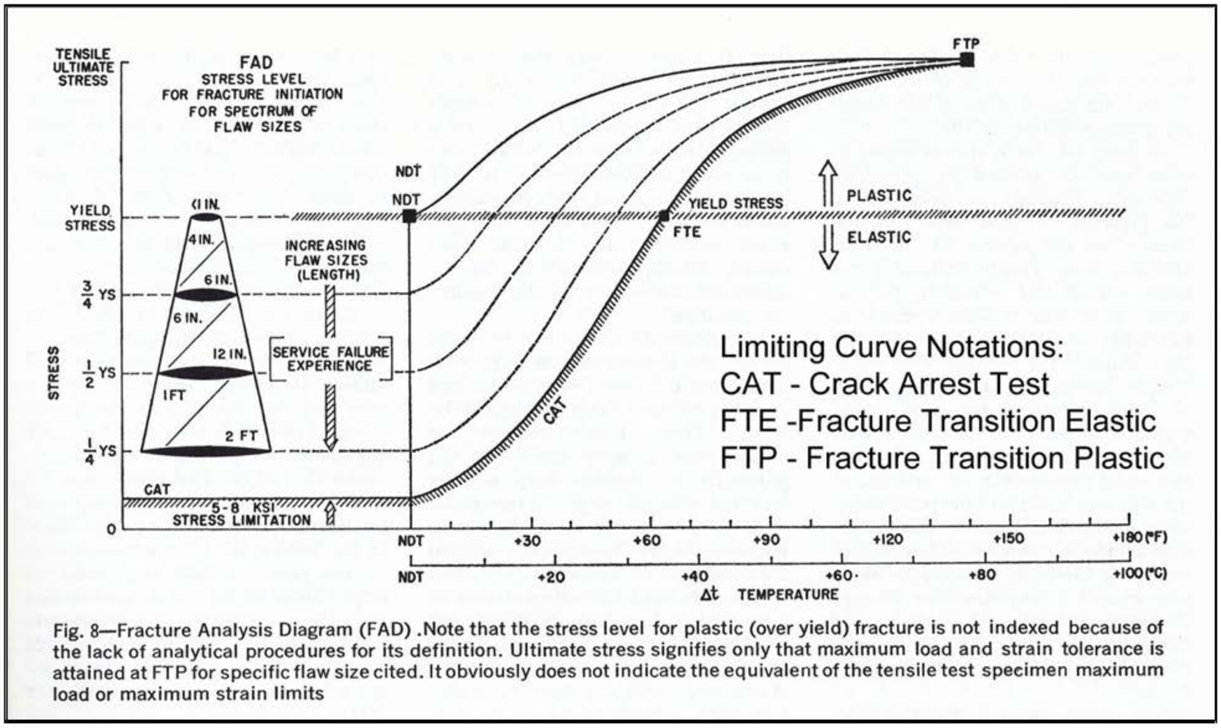


Figure 52 Fracture Analysis Diagram (Pellini, W.S., "Principles of Fracture-Safe Design – Part 1," *Welding Journal*, American Welding Society, March 1971.)

Comparison of Critical Crack Sizes

Load Case	Uniform Stress	Critical Crack Size		
		LEFM		Pellini FAD
		45 ksi-in$^{0.5}$	72.5 ksi-in$^{0.5}$	
	ksi	in	in	in
1	94.57	0.057	0.148	3.50
2	36.57	0.381	0.988	20.00
3	125.00	0.033	0.085	1.50

Figure 53 A comparison of critical crack sizes in high strength steel plate based upon fracture mechanics (LEFM) and the Fracture Analysis Diagram (Hallman, R.T., "Sherman Minton Bridge BS7910 Fracture Assessment and Commentary, Applied Mechanics, Prepared for the Kentucky Transportation Center, May 26, 2012)

Figure 54 Crack in H-girder (high strength steel) on I-65 Kennedy Bridge 22-1/2 long x 3/8” deep (HNTB, “Bridge Inspection Report: I-65 BRIDGE over the Ohio River,” Report to the Commonwealth of Kentucky Transportation Cabinet, Department of Highways, Division of Maintenance, May 1991).

Fracture mechanics and the FAD can be used to characterize the severity of flaws detected by NDE. They can also be used to determine inspection frequency and NDE test methods. In other cases, very small cracks have caused brittle fractures that may not be anticipated to cause failure by fracture mechanics unless all relevant factors are known (Figure 55). In the case of the Hoan Bridge detail, a combination of design factors (a weld attachment detail and three-girder span layout) lead to a near collapse of the bridge and temporary bridge closure. There was no physical flaw prior to crack formation and a running brittle failure of two girders, so no NDE method was practical — it was caused by a poor weld detail.

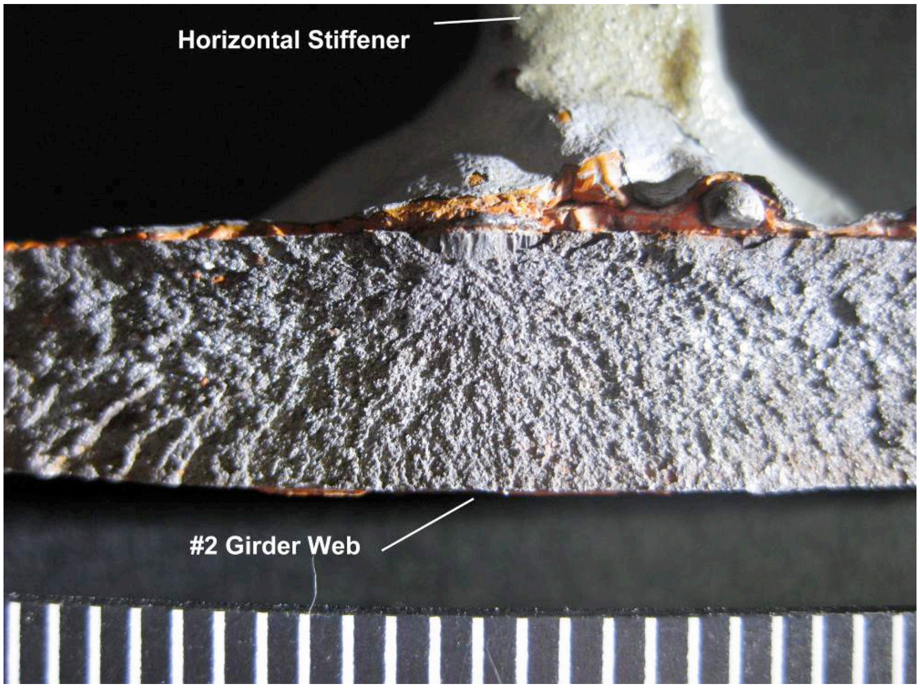


Figure 55 Fractured girder web with fracture origin (arrow) and surrounding fast (cleavage) fracture that severed the web (millimeter scale at bottom of picture)

As noted above, determining whether a flaw is a defect is challenging, even using fracture-mechanics analyses. Another approach is to address flaws, such as cracks, by agency policy. An agency policy could mandate that all cracks must repaired, or that certain types of cracks warrant repairs. The policy could also set an acceptable timeperiod between crack detection and repair. In some cases, crack detection can lead to an immediate decision related to closure or posting of a bridge. In the case of the Sherman Minton Bridge, the route was immediately shut down when fracture mechanics indicated a cracked tie-chord was at risk of fracturing. When the crack was detected in one of the I-275 Combs-Hehl Bridges, the bridge was immediately posted at a load limit of 6,000 lb. and truck traffic was diverted to other routes. The posting was not removed until the defective splice plates were replaced. No fracture analyses were performed before the posting. Non-crack (or crack-like) flaws found in structures (e.g., slag stringers or large porosity) may be assessed based upon size. In these cases, the impact of non-crack flaws may prove difficult to evaluate when making a repair decision. A welding engineer, fracture mechanic expert and/or metallurgist may need to be consulted when determining whether they pose a threat to structural integrity.

4. National Bridge NDE Survey

In 2016, KTC administered a national survey that asked state DOTs to identify the following: 1) their practice and use of NDE to inspect bridges, and 2) how NDE findings are incorporated into their decision-making process. The survey was distributed to all DOTs with the assistance of AASHTO. Appendix A includes the detailed survey summary. KTC received responses from 31 DOTs, although the number of responses for individual questions varied significantly.

Over half of the DOT respondents stated that their agencies routinely use NDE on steel bridges. The most common use of NDE is related to fracture-critical bridges, regardless of importance of routes carried. NDE is used on some redundant bridges but not as commonly as for the fracture-critical ones. Fracture-critical and redundant bridges with problematic structural details, or those with corrosion or other damage, are more likely to be inspected using NDE. Bridge pins/pin-and-hanger assemblies are components typically inspected using NDE.

NDE is commonly used on 24-month intervals, corresponding to biennial inspections and some fracture-critical ones. Several states have 48- and 72-month intervals. The most common factors prompting the discovery of anomalies (flaws) on structures occur during these inspections or activities monitoring existing flaws for growth or change in condition (both approximately 90% of the responses). Other significant factors prompting the use of NDE include the detection of flaws at similar locations on the same bridge or the discovery of flaws on other similar bridges (both over 50% of the responses).

PT, followed by MT, is the most common NDE method used by DOTs for most routine bridge inspection tasks. States also use UT, but this is less common than the two surface methods. AE is also used for some specific test requirements, including post-tensioning strands. UT (and to a lesser extend PAUT) are used for pin inspection.

For condition-specific NDE testing (non-routine circumstances due to existing problems or major concerns) all 7 candidate methods (PT, MT, ET, UT, PAUT, RT and AET) are used by DOTs on welds and other plate-type bridge elements (eyebars, gusset plates and hangers). Again, PT and MT are the most frequently used methods, followed by conventional UT. UT is often used for section loss measurements on eyebars and gusset plates. AET and UT are used on post-tensioning strands, including stay cables. UT and PAUT, along with MTC, are commonly used on pins and hangers.

DOTs have adopted NDE inspection standards from the American Welding Society (AWS) D 1.5 for welded components, American Society for Testing and Materials (ASTM) standards for specific tests (AET, MT, PT and RT), NHI guidance for inspection of fracture-critical members, American Society for Nondestructive Testing (ASNT) documents related to qualification of NDE personnel, and internal DOT documents.

Most of the responding DOTs (75%) rely on a mix of contract and in-house personnel to perform NDE. The remaining 25% use only in-house personnel. Only one DOT contracts out all of its NDE work. Sixty percent of the DOTs have certification/education/experience requirements for NDE personnel (both contractors/consultants and in-house personnel), while forty percent do not. Qualifications include ASNT (SNT-TC-1A), NHI training and in-house requirements (presumably for DOT personnel).

Among the responding DOTs, approximately half (55%) use in-house personnel to determine the NDE test requirements. The remaining agencies rely on mutual agreements between themselves and consultants. About 45% of the time, DOTs make follow-up decisions based on NDE findings while 55% of the time, decision-making responsibilities are shared between the consultants and in-house personnel. NDE is most commonly used for biennial inspections (including fracture-critical bridges) and other test intervals specified by DOTs, annual inspections or less depending upon specific circumstances. Most of the special tests used UT.

Routine/annual NDE cost data was sparse. Costs noted without explanation included $20,000 and $100,000. Other costs noted include:

- $150,000 every 5 years for routine pin inspections
- $200-250/each pin-hanger connection and $50-100 per crack for PT or MT
- Materials (presumably annually) $5,000/year and $50,000/year for routine inspections by consultants

For special inspections the cost data were also sparse:

- Inspection of a cable-stayed bridge over the Mississippi River ($1,164,000 total cost)
- Inspection of an 80-foot span in 2015 included $8,000 to UT of welds at 50 locations and access and traffic control costs of $3,000
- Costs of UT welds of an unknown bridge having high-strength QT steel ($14,000) not including traffic control and access equipment

All responding DOTs use NDE information to determine the need for follow-up actions (e.g., repairs). Typically, DOT central office maintenance and bridge/structures divisions are involved in the decision making.

NDE is used as part of structural health monitoring (SHM) systems by 31.6% of the DOTs. It is likely that AE monitoring is the mostly widely used NDE method given that it can be employed for continuous monitoring in conjunction with other SHM technologies such as strain gages and accelerometers.

DOTs are generally satisfied with the current level of information/training available for NDE. INDOT noted that it is investigating the systematic use of NDE on bridges. Several DOTs noted that on-line courses would be valuable, especially refresher courses on PT and MT. Other respondents commented that their NDE training needs are met by NHI courses. One DOT noted that current national standards/specifications for NDE are related to fabrication inspection and that similar specifications would be useful for inspection of in-service bridges. Several DOTs noted that there should be at least moderate training requirements for personnel doing NDE on bridges (including methods beyond PT and MT). Others recommended that the training should focus on actual bridge defects. Others recommended an executive course for NDE managers.

5. Decision Making Related to NDE

5.1 Options for Structural Inspections

Most DOTs act promptly to address flaws discovered by NDE, typically by eliminating the flaw or the threat that it poses. The ability of a bridge component to function when there is a flaw present is termed *damage tolerance*. In a number of instances, DOTs have tolerated out-of-plane bending flaws (e.g., cracks in floor beams of tied arch bridges). Even cracks in tensile areas of bridge girders have been left for some time if they are not thought to be growing fatigue cracks. The use of NDE in the structural inspection/ monitoring process relates to the situation being addressed and the perceived need.

There are 3 options for structural inspections:

1) Visual testing (VT)
2) Nondestructive testing (scheduled or incident-based)
3) Structural health monitoring (SHM) (16).

As previously noted, VT is used for biennial safety and fracture-critical inspections (conducted annually by KYTC). It has served as the backbone of bridge inspections. Since those inspections were mandated, its vigorous application has proven largely successful in preventing many bridge problems. DOTs are generally aware of its limitations and have attempted to augment it for routine inspections by providing inspectors with basic NDE tools (PT and MT).

DOTs do not use NDE indiscriminately for bridge inspections. In general, NDE is used when DOTs are concerned about the structural reliability of steel bridge components related primarily to the susceptibility of failure due to component fractures. Concerns can be based upon a variety of causes, including the discovery of cracking on a bridge component (higher if the component is an FCM), the discovery of flaws or surface blemishes that cannot be visually evaluated, surface indications found by PT or MT, problematic fatigue details (e.g. category E and E' weld details), details/designs/materials similar to problematic ones on other bridges and component damage due to corrosion or vehicular impacts. Locations where fatigue cracking can occur are well known (17). The behavior of a crack once it nucleates and grows, or grows from an existing flaw, is open to question, but NDE can be used to address this situation.

SHM entails the permanent or long-term use of sensors on bridges to continuously monitor stresses, strains, loads, deflections, displacements, vibrations and NDE activity such as AE monitoring. Sensors are coupled to data acquisition and telemetry devices that transmit the data to master computers for data storage and analysis; they can also trigger threshold alarms for DOT personnel at office locations or even on cell phones. Where known cracks are present, electrochemical sensing, crack growth sensors and AET are used to determine whether the cracks are experiencing subcritical crack growth. SHM installations can be targeted for specific bridge details/members or large-scale systems with able to remotely evaluate the overall reliability of the bridge, usually in near real time (Figure 56). The beneficial uses of SHM include monitoring overall structure performance, detection of overloads/crashes, detection of flaws or flaw activity, monitoring retrofits and determining abnormal conditions. Owner benefits include deferred capital expenditures (by being able to maintain bridges at current state of repair), risk and safety management, maintenance management, compliance with MAP-21 requirements and limiting political prioritization of projects (18). User benefits include enhanced safety and minimization of detours/postings. SHM should be considered when bridge risks (see below) require frequent periodic monitoring by conventional NDE that may be prohibitively expensive and continuous monitoring is more cost-effective.

(a) (b)

Figure 56 Structural health monitoring system to monitor: (a) a structural retrofit-uplift bearing; (b) data acquisition/telemetry cabinet

5.2 A Process to Address Specific Concerns

Where specific concerns exist, a five-phase process is proposed to address the use of NDE for evaluating the reliability of steel bridges. Those are:

1. Identify a problem or concern.
2. Determine effective NDE methods/test personnel to address the concern.
3. Apply NDE on the pertinent bridge/structural member in a timely manner.
4. Interpret the NDE findings.
5. Develop a remedial action (if warranted).

The first step begins with the identification of a problem or concern (e.g., discovery of a crack or other significant flaw) or a potential problem (e.g., a flaw indication, poor weld detail or discovery of a significant flaw at similar locations on a bridge or on similar bridges-even those in other states). In some cases, fatigue analysis can determine if NDE is warranted on specific bridge components of at-risk bridges. The next step is determining what actions are required for addressing a specific bridge (one containing the problem or potential problem). A determination must be made about whether the location/detail with the problem/potential problem is an isolated event (e.g., an impact to an overpass girder) or if other similar locations on the bridge are susceptible to a comparable problem. The discovery of cracks in several tie chord butt-welds on the I-64 Sherman Minton Bridge is an example of the latter situation. Subsequent NDE using ultrasonic testing revealed numerous additional cracks at similar locations on the Bridge. Strain gaging revealed that those cracks were not subject to live stresses sufficiently great to cause fatigue. The primary concern was the possibility of brittle failure at low temperatures.

Metallurgical analyses, depending on the nature of the problem, may be a necessary aid for determining follow-up inspection requirements. Metallurgical analysis was used to detect the improperly tempered ASTM A514 high yield strength quenched-and-tempered steel on the I-275 Combs-Hehl twin bridges. That analysis also revealed another problematic finding — plates had fractured from the interior face of the plates, and cracks extended to the exterior faces. The crack growth could not be detected visually until through-thickness long cracks were present. This finding contributed to the use of hardness testing to detect improperly heat-treated steel on the bridges rather than inspecting the plates for cracks using conventional NDE methods. It was assumed that only those plates would be prone to cracking. Prior to doing this, sample pieces of steel were taken from the steel plates identified by multiple field hardness tests (ultrasonic and impact hardness testing) as being defective. Those pieces were subjected to laboratory bench hardness tests and optically metallography to ascertain that they were made of defective steel. After completing the confirmation testing, the bad steel plates were eventually replaced or reinforced.

Another case involved cracking in the webs of fascia girders on KYTC bridges in the late 1980s (Figures 57, 58). The cracks were due to incomplete penetration butt-welds used to splice pieces of bar stock that comprised horizontal stiffeners welded to the exterior faces of the girders. Eventually, live loads caused the splice butt-welds to fracture due to fatigue. Those cracks traversed the stiffener-to-web fillet welds, causing the webs to develop unstable fractures that nearly parted the girders by the time that they were detected. Visual inspections of a few other bridges with similar features revealed growing fatigue cracks either in the stiffeners or migrating through the attachment fillet welds a short distance into the webs. Thereafter, an inspection program was instituted to identify problematic locations on many KYTC bridges with similar details. VT was used to locate growing cracks. It was supplemented with UT to locate problem locations where the partial penetration splice welds were located in the stiffeners. The inspection program detected all the other growing fatigue cracks before they caused significant cracking problems like those encountered in the first bridge. Retrofits were performed on the fascia girders to prevent any nucleating fatigue cracks in the stiffeners from growing into the webs (Figure 59). Those were applied everywhere the partial penetration butt welds were present in horizontal stiffeners whether they were cracking.

Figure 57 Major crack in fascia girder of the KY 117 bridge over I-24 in 1987

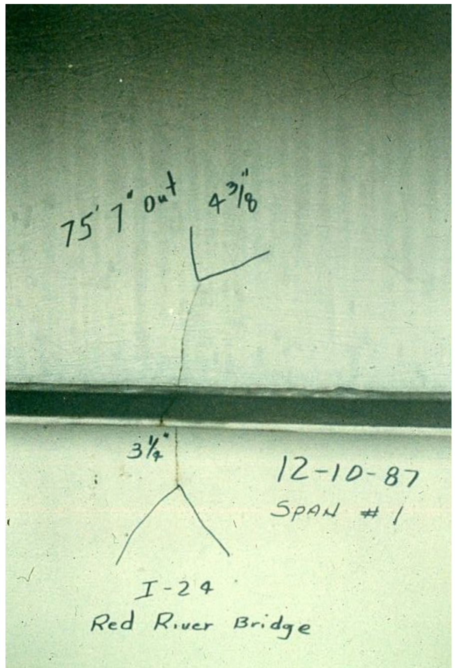


Figure 58 Fatigue crack growth in fascia girder web detected by VT before unstable fracture occurred

Figure 59 A check hole used to stop further fatigue crack growth in a fascia girder

Girder fractures were detected on the I-75 twin bridges over Lynn Camp Creek in Owsley County. Both bridges experienced similar fractures in 2012, and in the northbound bridge in 2014, some 45 years after they were placed in service. Subsequent failure analysis of the 2014 crack problem indicated that the fracture was initiated by a very small fatigue crack (approximately 0.2 inches long by about 0.03 inches deep). The crack occurred in a poor weld detail with close gaps between vertical and horizontal stiffeners and multiple intersecting fillet welds. Residual stresses and low steel toughness at low temperatures probably contributed to the unstable fracture of the girder. The small size of the critical crack indicated that the best option would probably be to retrofit all similar weld details on the two bridges to preclude further fractures. The situation was similar to the Hoan Bridge fracture problem in Milwaukee, Wisconsin, in 2000. In that case, no initial subcritical crack mechanism was needed as the bridge's girders fractured due to brittle pop-in cracks. Again, for that situation, NDE was not considered effective and the problematic weld details were rehabilitated.

NDE can be used to inspect for damage (cracking) caused by vehicle impacts (typically over-height vehicles impacting overpass bridges). This can be done immediately after the impact and also after a steel beam has been straightened. Other possible NDE uses are for potential damage from overloads and hardness testing of steel after a bridge fire (impact or rebound hardness testing). NDE can also be used to evaluate retrofits. AE has been used to evaluate continued out-of-plane cracking after the application of a retrofit . A major example of this was the use of AE on the I-5 Vietnam Veterans Memorial Bridge near Sacramento, California. An electro-chemical fatigue crack sensor can also be used for this purpose.

NDE offers the ability to reduce the concern (risk) of problems, primarily due to cracking. DOT officials must decide how, where, and when to perform the tests. Part of the how is to determine who should perform the testing in addition to selecting the NDE method(s). In some cases this may be determined based on a DOT's in-house testing capabilities. At KYTC routine field inspections incorporate VT and PT or MT. PT and MT are typically used when VT provides an indication that warrants further investigation. If those methods do not resolve a concern, other NDE methods are used. KTC can support KYTC by performing UT to investigate crack indications and size cracks in welded plate components. For more in-depth inspections using subsurface methods or AE, KYTC can utilize commercial NDE test firms.

NDE should be applied to all components/details of concern. If fatigue cracking is possible, strain gaging can be used prior to NDE work to limit its application to structural components where live stresses are sufficient to cause crack growth. There is a process used to evaluate potential fatigue cracks or locations where crack nucleation and growth are a concern. That occurs especially when the accumulated live loads on an AASHTO fatigue detail have exceeded the number of cycles under the fatigue limit of the detail (its design life). In that case, the detail is no longer considered to be operating in its safe life and should be governed by an NDE/fracture mechanics protocol.

Previously, KTC strain-gaged fatigue-prone structural details in steel bridges on extended weight coal-haul routes (19). The resulting equivalent stresses (obtained from rainflow stress cycle counting and Miner's Rule) were plotted on the applicable AASTHO S-N diagrams for the structural detail and the fatigue "damage" was determined. The number of equivalent stress cycles measured during the monitoring period were used to make assumptions about the total number experienced over the life of the structure (Figure 60). When it has been determined that a weld detail on a bridge component has exceeded its design life, NDE can be used to allow the continued safe use of the bridge component. Inspection intervals can be set to provide assurance that the bridge component containing the problematic detail will not fail.

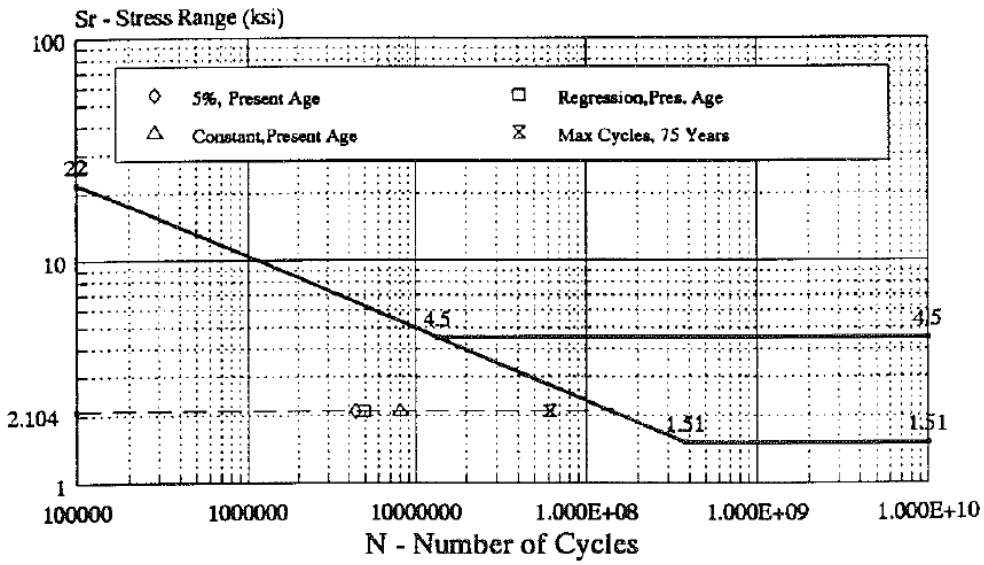


Figure 60 SN curve for AASHTO Category E fatigue detail with the endurance limit reduced to 1.51ksi based upon stress cycles that exceeded the 4.5 ksi endurance limit. The dashed line shows the Miner's equivalent stress range measured by strain gaging the detail on a bridge. The number of cycles are marked at that stress range level based upon stress cycles monitored during testing and various assumptions of total N over the current and projected 75-year life of the bridge.

When an NDE/fracture mechanics approach is used, it is assumed that a bridge component can contain a small flaw (e.g., crack of a specific size, α_o) that cannot be reliably detected by the NDE method/operator. Knowing the cyclic stress rate (e.g., Miner's equivalent stress for variable cyclic stressing), the growth of the hypothetical crack reliably missed by NDE can be predicted using the Paris fatigue crack growth law (20):

$$d\alpha/dN = C\ \Delta K^{m}$$

Where: ΔK = stress intensity factor range = $K_{max} - K_{min}$ (psi$\sqrt{in}$)
$d\alpha$ = change in crack length (inches)
dN = change in number of cycles
C, m = material constants.

Based on this calculation, follow-up inspections can be planned to ensure that the NDE method can be reapplied to detect a growing hypothetical crack of initial size α prior to it causing component failure (based upon fracture mechanics or other assumptions for critical crack size). Knowing K for α_o, the crack size missed by the NDE inspection (usually an assumed value), and K_{IC} for $\alpha_{critical}$, the crack size necessary to cause unstable tensile fracture, the number of stress cycles necessary to cause failure can be broadly estimated with the time relationship with dα/dN determined by strain gage monitoring of the component at the problematic detail. Strain gaging can be used to provide both Δσ, the equivalent live stress needed to compute ΔK, and the frequency of dN, which can be used to estimate the time, $T_{critical}$, necessary for α_o to grow to $\alpha_{critical}$ and cause component failure. Periodic re-inspections using the NDE method/operator can be scheduled at an interval necessary to detect a potential fatigue crack and ensure the component's structural reliability (usually < $T_{critical}/2$), giving the NDE method/operator two to three opportunities to detect a growing crack (21). This approach enables steel bridges to remain in service well beyond their normal design lives with NDE, ensuring structural reliability when no significant crack is present and allowing repairs to be effected before a growing fatigue crack can cause failure (Figure 61). A theoretical model for basing inspection frequency has been developed for detecting and sizing bridge defects (22). Another model predicts when NDE inspections should be performed based upon past inspection findings (23).

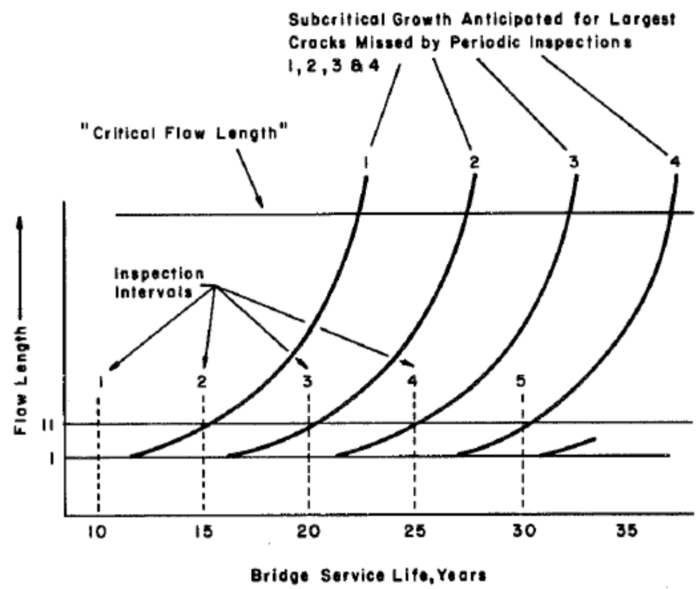


Figure 61 Life extension curve. At higher inspection sensitivity (reliable detection of smaller flaws — Flaw Length I), the inspection interval can be increased compared to a less sensitive inspection level (reliable detection of larger flaws — Flaw Length II) (Boisvert, B.W., Lewis, W.H. and Sproat, W.H., "Uniform Qualification of Military and Civilian Nondestructive Inspection Personnel," Lockheed-Georgia Co., Report No. LG81WP7254-003, September, 1981).

If there are concerns about brittle fracture and large cracks have been detected (even in locations where fatigue is not an issue) all large NDE indications must be identified and their type properly classified (e.g., cracks, voids, and others) to assess the situation and determine if follow-up actions are necessary and where exactly they must be applied. If a generic problem exists (e.g., the previously discussed horizontal stiffener weld cracking), all details on similar bridges may warrant inspection to ensure that problems do not arise on additional bridges.

Generally, it is best to fully characterize a flaw (type, location/size, active/inert) prior to deciding on the relevant follow-up action. This may not occur in a single inspection. Usually there is a progression in inspection, with test rigor being ratcheted up based upon preliminary findings. Eddy current testing can be used for surface investigations involving numerous surface discontinuities to attain greater accuracy in surface testing and productivity gains over PT and MT. It requires test equipment and experienced operators. UT and RT can be used to determine whether surface indications are actually cracks and more accurately determine their length than any of the surface methods. AE can be used to determine whether a crack or other flaw is experiencing sub-critical crack growth due to fatigue, corrosion fatigue or stress corrosion. The choice of NDE method(s) and testing approach depends upon its (their) ability to provide results that offer categorical answers related to agency concerns. The selection of a test protocol is determined by that capability, cost restraints and the time-dependent need for resolution of the DOT's concern. If test methods cannot classify flaws or fully address agency concerns additional test methods may be needed, including coring to extract the flaws and metallurgical evaluation of those in the laboratory.

Once all NDE indications have been located and fully characterized, the DOT must determine whether they require follow-up remedial actions. The resulting actions include:

- No further action
- Continued monitoring of existing flaws or problematic structural details (VT or other NDE method). Monitoring can incorporate NDE as part of a structural health monitoring system.
- Posting lower load limits on a bridge/diverting traffic from lanes of a bridge
- Elimination or minimizing potential threat posed by a flaw (repair)
- Eliminating problematic structural details
- Strengthening structural members/components
- Bridge closure/replacement

If NDE finds no flaw indications, it does not necessarily mean that follow-up NDE work will not be required at some point in the future if there is a possibility of subsequent sub-critical crack growth (e.g., by fatigue, corrosion fatigue or stress corrosion).

Detection of a critical flaw (criticality being based on the perception of DOT officials in some cases) usually results in the flaw(s) be fixed or problematic components being rehabilitated. The 2014 cracking in a girder of one of the I-75 twin bridges over Lynn Camp Creek was repaired, and the bridge was placed back in service without further NDE inspections or remedial work. In that case, KYTC officials relied on structural redundancy as a safeguard against potential cracking problems at other locations. Repairs can involve complete extraction of a flaw or placing check holes at the flaws' extremities (e.g., crack tips) to prevent possible crack growth or lapping with bolted cover plates to bridge a crack (and possibly reinforce the connection). For problematic details, welds can be removed and replaced with bolted connections, abrupt geometric transitions can be smoothed, rivets can be replaced with bolts, and flexible connections can be stiffened (among other repair options). The FHWA has a detailed manual on repairing fatigue crack problems in steel structures (24). In unusual cases involving problematic materials (e.g. the I-275 Combs-Hehl twin bridges), the material can be removed or reinforced by lapping with bolted cover plates.

In the case of the US 35 Silver Bridge that collapsed at Point Pleasant, West Virginia, investigators determined that the eyebars were made from brittle steel susceptible to corrosion cracking, and that the critical crack size for eyebar fracture was too small to be detected by NDE methods. The design of the bridge was such that a single eyebar failure could result in rapid bridge collapse. A sister bridge with similar features, the St. Marys, West Virginia bridge was decommissioned immediately after the Silver Bridge collapse and subsequently dismantled as it was economically impractical to replace the defective eyebars on that bridge.

In 2010, CALTRANS let a contract to use AE monitoring on cracks detected on eyebars of a truss span on the Oakland Bay Bridge. The monitoring operation let CALTRANS operate the bridge with the cracked eyebars while work was undertaken on a replacement span. AE has also been used to continuously monitor stay cables on several bridges around the US.

When no special concerns are present, a DOT can scope its inspections to used NDE methods outside of VT, PT or MT by using the following three-step process (25):

1) Determine what can go wrong and the likelihood of +those possibilities.
2) Assess the consequence of those potential events.
3) Determine the inspection interval and scope of inspection.

A rigorous review of these factors can provide a realistic framework for applying NDE methods appropriately — not based upon a method's cost, inspector expertise or routine availability.

5.3 Risk-Based Inspections

While the previous model can address specific concerns, the systematic application of NDE on steel bridges should be risk-based and incorporate NDE where it can reduce risk at the designated inspection intervals. Many sectors are adopting this approach, including the petroleum and aircraft industries. Risk of a problematic event (e.g., catastrophe or temporary loss of service) is typically expressed mathematically by the equation:

Risk = Probability of Event x Consequences of Event

For bridges, the probability of the event can address loss of service and ensuing motorist inconvenience due to delays or detours or, in the worst case, it can involve collapse and loss of life. The former is more common and can be very expensive if user costs are incorporated into the total cost of an incident. The University of Kentucky Transportation Research Program (antecedent to the Kentucky Transportation Center) published a report that addressed risk factors for bridges (26). It provided a simple procedure to estimate risk, addressing primarily bridge collapse as a means of deriving acceptable NDE expenditures to "buy down" that risk. It focused on the probability of bridge collapses, which are typically low probability-high consequence events (27). The total cost of the US 35 Point Pleasant Bridge collapse in 1967 was estimated at $175,000,000 (28) and the cost of the 2007 collapse of the I-35 collapse in Minneapolis was estimated at $460,000,000 (29). It did not speak to the loss of service by bridges that did not collapse but were either shut down, requiring detours, or restricted in their load postings or number of motorist lanes. In 2002, KTC developed a software program to calculate total costs to motorists due to highway construction projects. It accounted for delays at the work site and costs for using detours (30). That approach is also applicable to loss of service from bridge problems.

The use of NDE for in-depth inspections and the immediate findings they produce can result in considerable motorist inconvenience/expense. In 2008, during the NDE work on the I-275 Combs-Hehl twin bridges, significant traffic backups occurred during rush hours due to single lane closures on both bridges. KYTC district officials stated that the number of accidents increased threefold compared to normal operation of the bridges. When cracks were found in the northbound bridge, there were significant losses by truckers making time-consuming detours to avoid the bridge. To address the many trucks that disregarded the low (6,000-lb) posting on the bridge, KYTC had to obtain police oversight on the bridge 24/7 for several months, which cost tens of thousands of dollars. During the crack issue on the I-75 bridge over Lynn Camp Creek (northbound), one travel lane on the bridge was closed for several weeks until repairs to a cracked girder could be effected. This caused significant traffic backups on I-75 and long motorists delays. The cost to motorists for 2011 closure of the I-64 Sherman Minton bridge for repairs was estimated at $438,000 per day (31). Bridge closures, postings and lane restrictions are of significance in that they are more frequent than bridge collapses and their costs, especially those resulting from motorist inconvenience, are significant. Both consequence types (collapse and disablement/motorist costs) need to be evaluated to assess the risks of steel bridges to service-based deterioration.

Risk assessments can be qualitative (using engineering judgement and experience), quantitative (using logic models and probability) or semi-quantitative, integrating both of those approaches (32). The RBI process is shown in Figure 62. Risk for manufactured/fabricated items including bridges can be viewed as a standard failure probability versus time or the *Bathtub* curve (Figure 63). The curve consists of three distinct zones representing variations in performance based upon item age and service exposure. The initial portion of early life shows a decreasing rate of failure. Failures in this portion are termed *infant mortality* or *burn-in* failures typically representing fabrication or severe design deficiencies (e.g., the I-79 Neville Island, Pennsylvania, bridge closure due to cracking in 1979). The major portion of the service life is represented by a minimum failure rate. Failures occurring in this portion of the curve are termed *catastrophes*. These are typically due to unforeseen cumulative damage (US 35 Point Pleasant bridge) or unusual sets of circumstances (I-35 Minneapolis bridge). The last portion represents increasing failure rates due to cumulative damage resulting from normal service over an extended period. Those are termed *wear out* or *end of life* failures. Other researchers have proposed using this behavior and qualitative or semi-qualitative risk assessments to develop risk-based inspection programs (op. cit. 25).

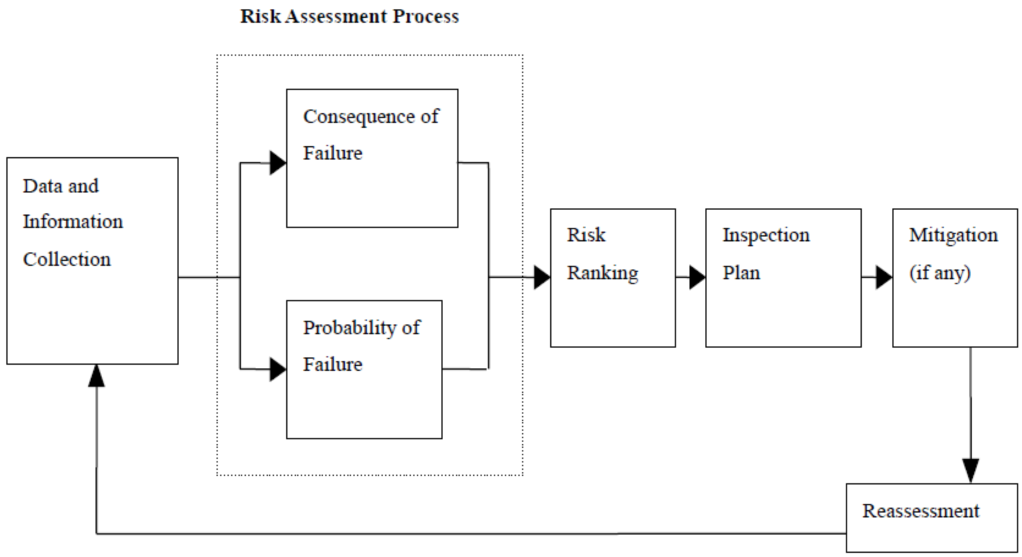


Figure 62 The Risk-Based Inspection Process (Kaley, L. and Henry, P., http://www.trinity-bridge.com/sites/default/files/presentations/2009%20Summit%20A%20Quantitative%20Solution%20Made%20Practical_v11.pdf).

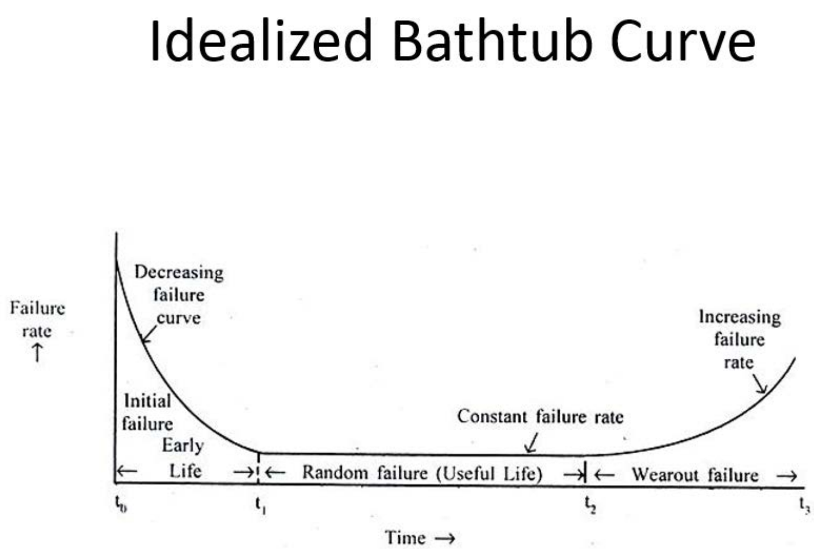


Figure 63 Failure probability versus time for viewing age effect of manufactured and fabricated components including bridges. In the main, this curve represents the results of normal wear and tear with random failures due to abusive use (overloads), design flaws and manufacturing & fabrication defects.

The FHWA recently provided the following information:

"The FHWA published the Final Rule for Asset Management in late October. This can be found at https://www.fhwa.dot.gov/tpm/rule.cfm along with other information related to Transportation Performance Management. The Asset Management Rule is not prescriptive on bridge inspection, but describes how States should manage their assets over their life, focusing on replacement, rehabilitation, preservation, and maintenance.

MAP-21 required the FHWA to update the NBIS and consider a risk-based approach to determining the inspection frequency. This work is ongoing and a Notice of Proposed Rulemaking has yet to be published. Until the NBIS is updated or FHWA issues interim guidance, the frequencies allowed by the NBIS are what States need to work with.

Many States consider NDE as part of in-depth inspections and the NBIS requires the State to determine the level and frequency of these inspections. This may be an avenue worth pursuing that would be allowed under today's NBIS (33)."

Reliability-Based Bridge Inspection Practices rather than 24-month intervals based on safety and reliability of bridges by determining appropriate inspection practices for bridges would consider the structure type, age, condition, importance, environment, loading, prior problems, and other characteristics of the bridge (34). The appropriate use of NDE should be part of a RBI approach including its potential for decreasing risks.

6. Conclusions

KYTC is currently employing NDE in a manner similar to most DOTs. District bridge inspectors carry Penetrant Testing (PT) and/or Magnetic Particle Testing (MT) supplies/equipment and use them to test surface defects. Also, Ultrasonic Testing (UT), Radiographic Testing (RT), and Acoustic Emission Testing (AET) have been used to evaluate or size flaws both on an as-needed basis, or on inspection and experimental projects with several private consultants and university research centers. KYTC has reviewed the NDE findings to inform repair decisions. Expert opinions by others suggest that the cheaper tests were faster and easier to perform, but the costlier methods were more accurate and reliable (35). If KYTC adopts a risk-based approach to bridge inspections, those factors should be taken into account.

Because KYTC's bridge inventory (not just steel bridges) is aging, problems associated with mounting damage will increase. Sufficient funds will not be available to replace a major portion of the existing bridges, and in-service bridges will need to remain in service for decades to come — many beyond their original design service lives. NDE will need to play a more integral role to ensure that those bridges retain their structural integrity and can continue to operate safely. Nationwide, the concept of risk management is becoming more prominent and viable approaches to RBI have been formulated. At some point, DOTs will begin to adopt risk-based bridge inspections incorporating NDE.

7. Recommendations

The following steps are recommended:

1) Offer formal training to KYTC inspectors who use PT and MT from firms primarily involved in NDE training.
2) Maintain a rapid respond "first look" NDE capability either through KTC or outside consultants.
3) Investigate the development of a risk-based inspection program focusing on both inspection frequency and enhanced inspection (NDE) tools.

References

1. http://www.fhwa.dot.gov/research/tfhrc/labs/nde/
2. National Association of Corrosion Engineers Website, http://www.nace.org/Corrosion-Central/Industries/Highways-and-Bridges/
3. Wikipedia Metalworking - https://en.wikipedia.org/wiki/Rolling_(metalworking)
4. United States Steel Corporation, "The Making, Shaping and Treating of Steel, American Association of Iron and Steel Engineers, 10th Edition, 1985, (pp. 730-732, 757, 758).
5. Fisher, J.W., "Inspecting Steel Bridges for Fatigue Damage," Lehigh University, Fritz Laboratory, Report 72-3 FHWA/PA-81/003, March 1981.
6. Boisvert, B.W., Lewis, W.H. and Sproat, W.H., "Uniform Qualification of Military and Civilian Nondestructive Inspection Personnel," Lockheed-Georgia Co., Report No. LG81WP7254, September 1981.
7. ETher NDE Eddy Current Solutions, http://www.etherndе.com/probes/weld-probes/inspection-process
8. Lamtenzan, D., G. Washer, and Lozev, M., "Detection and Sizing of Cracks in Structural Steel Using the Eddy Current Method," FHWA, Nondestructive Evaluation Validation Center, Report No. FHWA-RD-00-018, April 1996-June 1997.
9. Wilkinson, S. and Duke, S.M., "Comparative Testing of Radiographic Testing, Ultrasonic Testing and Phased Array Advanced Ultrasonic Testing," Non Destructive Testing Techniques in Accordance with the AWS D 1.5 Bridge Welding Code, University of South Florida, Grant BDK84-977-26, February 28, 2014.
10. Kosnik, D.E. and Marron, D.R., "Acoustic Emission Evaluation of Retrofits on the I-80 Bryte Bend Bridge Sacramento, CA, Infrastructure Technology Institute, Northwestern University, Acoustic Emission Working Group, Advances in Acoustic Emission, 2007.
11. Ghorbanpoor, A. and Benish, N., "Non-Destructive Testing of Wisconsin Highway Bridges – Final Report," University of Wisconsin, Milwaukee, March 2003.
12. FHWA Nondestructive Testing Website, https://fhwaapps.fhwa.dot.gov/ndep/
13. Iowa State University NDT Resource Center, https://www.nde-ed.org/GeneralResources/MethodSummary/MethodSummary.htm
14. Washer, G., "Developments for the non-destructive evaluation of highway bridges in the USA," NDT&E International, Vol. 31, No. 4, 1998.
15. Youshaw, R.A., "A Guide for Ultrasonic Testing and Evaluation of Weld Flaws, "U.S. Naval Ordinance Laboratory, Report No. SSC-213, 1970.
16. Achenbach, J.D., "Quantitative Non-destructive Evaluation and Structural Health Monitoring for Structural Safety and Durability," Northwestern University McCormick Presentation at the University of Miami, November 4, 2013.
17. Haghani, R., Al-Emrani, M. and Heshmati, M., "Fatigue-Prone Details in Steel Bridges," Buildings, Volume 2, November 2012.
18. Floyd, R.L., "Strain-Based Structural Health Monitoring-An Owner's Perspective," TRB Webinar, October 7, 2015.
19. Hopwood, T., Hogan, K.J. and Oberst, C.M., "Stress Evaluation of Welded Steel Bridges on Coal-Haul Routes," Kentucky Transportation Center, Report No. KTC-93-14, May 1993.
20. Steele, J.M. and Lam, T.C., "Avoiding Catastrophic Fatigue Failures," Machine Design, January 6, 1983.
21. A Landscape for the Future of NDT in the UK Economy, www.materialsktn.net.

22. Sheils, E, O'Conner, A., Schoefs, F. and Breyesse, "Investigation of the effect of the quality of inspection techniques on the optimal inspection interval for structures," Structure and Infrastructure Engineering, Vol 8, June 2012.
23. Haldar, A. and Zhao, Z., "Fatigue Reliability Evaluation, Updating and Maintenance of Steel Bridge Using Nondestructive Inspections (NDI)," Structural reliability in bridge engineering: design, inspection, assessment, rehabilitation, and management, October 2-4, 1996.
24. "Manual for Repair and Retrofit of Fatigue Cracks in Steel Bridges," Federal Highway Administration, Report No. FHQA-1F-13-020, March 2013.
25. Washer, G., Nassrollahi, M., Applebury, C., Connor, R., Ciolko, A., Kogler, R., Fish, P. and Forsyth, D., "Proposed Guideline for Reliability-Based Bridge Inspection Practices," Transportation Research Board, Report No. NCHRP 782, August 2014.
26. Hopwood, T. and Deen, R.C., "Periodic Nondestructive Evaluation of In-Service Metal Bridges," University of Kentucky Transportation Research Program, Report No. 84-4, March 1984.
27. "Optimizing the Inspection Process," Nondestructive Testing Information Analysis Center Newsletter, San Antonio, TX, February, 1976.
28. Gerhard, J. and Haynie, F.H., "Air Pollution Effects on Catastrophic Failure," National Environmental Research Center, Triangle Park, North Carolina, Report No. EPA-605/3-74-009, November 1974.
29. http://thinkreliability.com/case_studies/root-cause-analysis-of-the-i-35-bridge-collapse/
30. Rister, B. and Graves, C., "The Cost of Construction Delays and Traffic Control for Life-Cycle Cost Analysis of Pavements," Kentucky Transportation Center, Report No. KTC-02-07/SPR 197-99 & SPR 218-00-1F, March 2002.
31. Sherman Minton Rehabilitation Executive Briefing, Bridge Project Team, September 2011.
32. Kaley, L. and Henry, P., http://www.trinity-bridge.com/sites/default/files/presentations/2009%20Summit%20A%20Quantitative%20Solution%20Made%20Practical_v11.pdf
33. Correspondence from Shay Burrows (FHWA) to Theodore Hopwood II, dated November 30, 2016.
34. Washer, G., Connor, R.J., Ciolko, A., Kogler, R., Fish, P. and Forsyth, D., "Proposed Guideline for Reliability-Based Bridge Inspection Practices, Transportation Research Board, Report No. 782, 2014.
35. Hesse, A., Atadero, R. and Ozbeck, M., Using Expert Opinion to Quantify Accuracy and Reliability of Nondestructive Evaluation of Bridges, Mountain-Plains Consortium, Report No. MPC 15-288, August 2015.

Appendix

Summary of KTC Survey of DOTs on the Use of NDE to Inspect Existing Steel Bridges

Question 1
Does your agency use nondestructive evaluation on a routine basis?

Answer Options	Response Percent	Response Count
Yes --> Question 2	54.8%	17
No --> Question 4	45.2%	14
	answered question	31
	skipped question	0

Question 2
What structures are tested?

Answer Options	Response Percent	Response Count
a. Fracture-critical on major routes?	46.7%	7
b. Fracture-critical on all routes?	60.0%	9
c. Fracture-critical with significant corrosion/damage?	80.0%	12
d. Redundant with problematic details?	73.3%	11
e. Redundant on major routes?	26.7%	4
f. Redundant with significant corrosion/damage	60.0%	9
g. Post-tensioned, cable stayed or suspension bridges?	40.0%	6
h) Other? (See below)	33.3%	5
	answered question	15
	skipped question	16

Response	h) Other? (explain)
1	Pin and Link assemblies
2	U/T of all pin-n-hanger bridges during routine inspection. U/T of anchor bolts for bolted on concrete bridge railing during the routine inspections. Dye-penetrant & mag particle as needed for identifying cracks in steel members (more so fracture critical bridges). Impact Echo for detecting delaminations in concrete bridge decks - not routine as of right now, but we are developing a process.
3	Pins
4	Pins on trusses and pin and hanger bridges
5	any steel bridge with suspect/possible crack(s)

Question 3
What is the frequency of testing?

answered question	14
skipped question	17

Number of Responses	(Months)
12	24
2	48
3	72

Question 4

What factors will prompt your agency to use nondestructive evaluation?

Answer Options	Response Percent	Response Count
a) Discovery of probable anomaly during biennial safety inspections or arm's length visual inspection	88.9%	24
b) Previously detected problems/flaws at similar locations on a bridge	59.3%	16
c) Monitoring a previously detected flaw for growth or change in condition	88.9%	24
d) Problems encountered with similar agency bridges or nationally on similar bridges	51.9%	14
e) Problems revealed by non-agency persons working on or observing the bridge (e.g. painters or motorists)	25.9%	7
f) None, the agency only uses visual inspection for existing bridges and steel structures	3.7%	1
g) Other (See Below)	18.5%	5
	answered question	27
	skipped question	4

Responses	g) Other (please specify)
1	*Annual not Biennial inspection. NDE used: IR on delams over traffic, GPR, Scope Reviews (GPR, IR on heavy trafficked wearing surface)
2	Planned monitoring of complex bridges for in-depth inspections
3	Policy - Inspect all pins every 24 months by UT
4	Inspection of members not accessible for visual inspection such as bridge pins. GPR and infrared scanning of bridge decks for rehabilitation projects.
5	We will probably use NDT on deck repairs routinely

Question 5

For routine NDE use on bridges, what NDE methods are used?

a) Welded bridges

Answer Options	Acoustic Emission (AE)	Radiographic Testing (RT)	Dye Penetrant Testing (PT)	Eddy Current Array Testing (ECA)	Eddy Current Testing (ECT)	Magnetic Flux Leakage (MFL)	Magnetic Particle Testing (MT)	Phased Array Ultrasonic Testing (PAUT)	Ultrasonic Testing (UT)	Response Count
i. Web & flange transition butt welds	0	0	3	0	0	0	1	0	1	4
ii. Web-to-flange fillet welds	0	0	3	0	0	0	2	0	1	4
iii. Gusset plate-to-web fillet welds	0	0	4	0	0	0	2	0	0	4
iv. Stiffener-to-web or flange fillet welds	0	0	4	0	0	0	2	0	0	4
v. Horizontal stiffener splice welds	0	0	4	0	0	0	2	0	0	4
vi.Cover plate welds	0	0	4	0	0	0	2	0	0	4
vii. Diaphragm-to-web or flange welds	0	0	4	0	0	0	2	0	0	4
viii. Out-of-plane/distortion cracking	0	0	6	0	0	0	4	0	1	7
ix. Field repairs/retrofits	0	0	1	0	0	0	1	0	0	2
x. Location of crack tips in plate/welds	0	0	6	0	0	0	5	1	1	8
xi. Other	0	0	1	0	0	0	0	0	0	1
Other (please specify)										2
									answered question	8
									skipped question	1

Comments	Other (please specify)
1	These NDE methods are used when cracks are suspected. They may be used at any of the locations identified in the right hand column when cracks are detected, but not when everything looks okay.
2	Other than visual inspection on a routine basis, we do not perform any NDE routinely unless we can see or are aware of cracking or severe deterioration.

b) Other plate-type bridge elements										
Answer Options	Acoustic Emission (AE)	Radiographic Testing (RT)	Dye Penetrant Testing (PT)	Eddy Current Array Testing (ECA)	Eddy Current Testing (ECT)	Magnetic Flux Leakage (MFL)	Magnetic Particle Testing (MT)	Phased Array Ultrasonic Testing (PAUT)	Ultrasonic Testing (UT)	Response Count
i Eyebars (cracking)	1	0	4	0	0	0	0	0	2	5
ii. Eyebars (corrosion section loss)	1	0	2	0	0	0	0	0	0	2
iii. Gusset plates (cracking)	1	0	6	0	0	0	3	0	0	7
iv. Gusset plates (corrosion section loss)	1	0	2	0	0	0	0	0	1	3
v. Hangers (cracking)	1	0	5	0	0	0	2	0	1	6
vi. Hangers (corrosion section loss)	1	0	2	0	0	0	0	0	1	3
vii. Other	1	0	1	0	0	0	0	0	0	1
Other (please specify)										0
									answered question	8
									skipped question	1

c) Wires (suspenders, suspension bridge wires, post-tensioning strands)

Answer Options	Acoustic Emission (AE)	Radiographic Testing (RT)	Dye Penetrant Testing (PT)	Eddy Current Array Testing (ECA)	Eddy Current Testing (ECT)	Magnetic Flux Leakage (MFL)	Magnetic Particle Testing (MT)	Phased Array Ultrasonic Testing (PAUT)	Ultrasonic Testing (UT)	Response Count
i. Suspenders-helical strand & wire rope (cracking)	0	0	0	0	0	0	0	0	0	0
ii. Suspenders-helical strand & wire rope (corrosion)	0	0	0	0	0	0	0	0	0	0
iii. Main cables-suspension bridges (cracking)	0	0	0	0	0	0	0	0	0	0
iv. Main cables-suspension bridges (corrosion)	0	0	0	0	0	0	0	0	0	0
v. Post-tensioning strands including stay cables (cracking)	1	0	0	0	0	0	0	0	0	1
vi. Post-tensioning strands including stay cables (corrosion)	0	0	0	0	0	0	0	0	0	0
Other (See Below)										0
									answered question	1
									skipped question	8

d) Pins

Answer Options	Acoustic Emission (AE)	Radiographic Testing (RT)	Dye Penetrant Testing (PT)	Eddy Current Array Testing (ECA)	Eddy Current Testing (ECT)	Magnetic Flux Leakage (MFL)	Magnetic Particle Testing (MT)	Phased Array Ultrasonic Testing (PAUT)	Ultrasonic Testing (UT)	Response Count
i. Bearing pins (cracking)	0	0	0	0	0	0	0	1	5	5
ii. Bearing pins (corrosion)	0	0	0	0	0	0	0	0	2	2
iii. Hanger/eyebar pins (cracking)	0	0	0	0	0	0	0	2	8	8
iv. Hanger/eyebar pins (corrosion/fretting)	0	0	0	0	0	0	0	0	4	4
Other (please specify)										1
answered question										8
skipped question										1

Responses	Other (please specify)
1	These NDE methods are used in FC inspections only.

e) Other steel bridge components		
Answer Options	**Response Percent**	**Response Count**
Acoustic Emission (AE)	0.0%	0
Crack Propagation Gage (CPG)	0.0%	0
Dye Penetrant Testing (PT)	50.0%	3
Eddy Current Array Testing (ECA)	0.0%	0
Eddy Current Testing (ECT)	0.0%	0
Magnetic Flux Leakage (MFL)	0.0%	0
Magnetic Particle Testing (MT)	50.0%	3
Phased Array Ultrasonic Testing (PAUT)	0.0%	0
Ultrasonic Testing (UT)	16.7%	1
Other (please specify)	16.7%	1
	answered question	6
	skipped question	3

Responses	Other (please specify)
1	We will use PT or MT if we see a crack in the structural steel. We do not use it routinely on all welds or connections

Question 6

For condition-specific (non-routine circumstances due to existing problems or major concerns) what NDE methods does your agency commonly use?

a) Welded bridges

Answer Options	Acoustic Emission (AE)	Radiographic Testing (RT)	Dye Penetrant Testing (PT)	Eddy Current Array Testing (ECA)	Eddy Current Testing (ECT)	Magnetic Flux Leakage (MFL)	Magnetic Particle Testing (MT)	Phased Array Ultrasonic Testing (PAUT)	Ultrasonic Testing (UT)	Response Count
i. Web & flange transition butt welds	0	3	13	0	1	0	12	1	7	18
ii. Web-to-flange fillet welds	0	0	14	0	1	1	15	0	3	19
iii. Gusset plate-to-web fillet welds	0	0	15	0	1	0	14	0	3	19
iv. Stiffener-to-web or flange fillet welds	0	0	14	0	1	1	16	0	3	20
v. Horizontal stiffener splice welds	0	0	13	0	2	0	10	0	4	17
vi. Cover plate welds	0	0	16	0	1	0	14	0	5	21
vii. Diaphragm-to-web or flange welds	0	0	12	0	1	0	14	0	2	17
viii. Out-of-plane bending	0	0	8	0	2	0	12	1	2	13
ix. Field repairs/retrofits	0	4	9	0	2	1	15	0	8	18
x. Location of crack tips and sizing in plate/welds	0	0	14	0	2	1	11	0	4	21
xi. Other	1	0	0	0	0	0	0	0	0	1
Other (See Below)										3
									answered question	21
									skipped question	10

Responses	Other (please specify)
1	NDE used on known issues or crack indications.
2	Acoustic Emission monitoring of structure that been retrofitted twice for fatigue cracking.
3	Ground penetrating radar

b) Other plate-type bridge elements

Answer Options	Acoustic Emission (AE)	Radiographic Testing (RT)	Dye Penetrant Testing (PT)	Eddy Current Array Testing (ECA)	Eddy Current Testing (ECT)	Magnetic Flux Leakage (MFL)	Magnetic Particle Testing (MT)	Phased Array Ultrasonic Testing (PAUT)	Ultrasonic Testing (UT)	Response Count
i. Eyebars (cracking)	0	0	9	0	1	0	7	1	2	13
ii. Eyebars (corrosion section loss)	0	0	1	0	0	0	1	1	8	9
iii. Gusset plates (cracking)	0	0	10	0	2	0	12	0	1	15
iv. Gusset plates (corrosion section loss)	0	0	2	0	0	0	2	0	10	12
v. Hangers (cracking)	0	0	8	0	2	0	6	2	5	15
vi. Hangers (corrosion section loss)	0	0	2	0	0	0	1	2	10	12
vii. Other	0	0	1	0	0	0	1	0	0	1
Other (please specify)										2
									answered question	17
									skipped question	14

Responses	Other (please specify)
1	A, B, and C Scan UT
2	No eyebars on State System

c) Wires (suspenders, suspension bridge wires, post-tensioning strands

Answer Options	Acoustic Emission (AE)	Radiographic Testing (RT)	Dye Penetrant Testing (PT)	Eddy Current Array Testing (ECA)	Eddy Current Testing (ECT)	Magnetic Flux Leakage (MFL)	Magnetic Particle Testing (MT)	Phased Array Ultrasonic Testing (PAUT)	Ultrasonic Testing (UT)	Response Count
i. Suspenders-helical strand & wire rope (cracking)	0	0	0	0	0	0	0	0	1	1
ii. Suspenders-helical strand & wire rope (corrosion)	0	0	0	0	0	0	0	0	1	1
iii. Main cables-suspension bridges (cracking)	0	0	0	0	0	0	0	0	1	1
iv. Main cables-suspension bridges (corrosion)	0	0	0	0	0	0	0	0	1	1
v. Post-tensioning strands including stay cables (cracking)	3	0	1	0	0	1	0	1	3	6
vi. Post-tensioning strands including stay cables (corrosion)	1	0	0	0	0	1	0	0	2	4
Other (See Below)										3
									answered question	6
									skipped question	25

Responses	Other (please specify)
1	Visual inspection of all cables and wires.
2	iii and iv. not common but recently used on our only remaining suspension bridge leading up to and through a rehabilitation project. For Cable Stayed cables we have used pull of tests and string-line vibration tests.
3	N/A

d) Pins

Answer Options	Acoustic Emission (AE)	Radiographic Testing (RT)	Dye Penetrant Testing (PT)	Eddy Current Array Testing (ECA)	Eddy Current Testing (ECT)	Magnetic Flux Leakage (MFL)	Magnetic Particle Testing (MT)	Phased Array Ultrasonic Testing (PAUT)	Ultrasonic Testing (UT)	Response Count
i. Bearing pins (cracking)	1	0	2	0	0	0	1	2	13	16
ii. Bearing pins (corrosion)	1	0	1	0	0	0	0	1	9	11
iii. Hanger/eyebar pins (cracking)	0	0	1	0	1	0	4	2	13	17
iv. Hanger/eyebar pins (corrosion/fretting)	0	0	0	0	0	0	0	2	10	10
Other (See Below)										2
									answered question	20
									skipped question	11

Responses	Other (please specify)
1	Visual inspection of bearing pins.
2	I and ii. depending upon access. UT preferred but if no access to cross-section then PAUT from the side/shank.

Other steel bridge components		
Answer Options	Response Percent	Response Count
Yes	11.1%	2
No	88.9%	16
If Yes, please list components, (damage to be evaluated) and associated NDE methods		2
	answered question	18
	skipped question	13

Number	If Yes, please list components, (damage to be evaluated) and associated NDE methods
1	Ultrasonic thickness testing of any corroded component.
2	If determined necessary.

Question 7

List the specifications, standards and guidance documents used for bridge NDE.

Answer Options	Response Count
	17
answered question	**17**
skipped question	**14**

Number	Responses
1	AWS D1.5 for welding. In-house procedures for remainder.
2	We have our own written procedures for NDT methods used on in-service bridges. For welding related inspection AWS D1.5 is used.
3	NCHRP, FHWA and AASHTO
4	ASNT's Nondestructive Testing Handbook, Volume Two, Liquid Penetrant Test, Volume 6, Magnetic Particle Testing; MIL-I-25135E-Inspection Materials, Penetrant; ASTM Penetrant Documents; ANSI/AASHTO/AWS Bridge Welding Code D1.5: radiographic - VTM-29 magnetic particle - VTM 31;ASNT-TC-1A - Acoustic Emission (Level 2), ASTM E2374, "Standard Guide for Acoustic Emission System Performance Verification", ASTM E16 "Standard Method for Primary Calibration of Acoustic Emission Sensors"
5	Some internal documentation, A NDE class held by FHWA
6	ASNT Level II,CWI
7	Inspection personnel utilizing dye penetrant are trained by the NHI course 130078 Fracture Critical Inspection Techniques for Steel Bridges and those utilizing Ultrasonic Testing are trained by outside agency personnel to at least the ASNT UT Level II.

Number	Response Text
8	With the exception of dye-penetrant testing, all the other NDT is completed by consultants as per the following: ASTM E-709 for mag particle, ASTM E1417 & E165 for dye-penetrant and ASNT, SNT-TC-1A, Supplement C for mag particle, eddy current and ultrasonic testing
9	ASNT AWS-Bridge Welding Code, ASNI

10	AASHTO
11	AWS D1.5.ASTM Standard, FHWA Guidelines
12	AWS, ASNT and FHWA standards/documents used as guidance documents
13	See Chapter 21: https://drive.google.com/file/d/0B8QRVMpaE6oYWTg3WU5ISDhkRGM/view
14	We have very limited information in our Policy and Procedure Manual. Inspectors are required in the field to make calls on determining what is needed to identify cracks. Major section loss checks or other special tests that require major field time are determined and scheduled in the Central Office.
15	ASTM Test methods for dye penetrant, AWS Welding Code and Bridge Inspectors Reference Manual (BIRM)
16	ANSI/ASNT CP-189-2011, AWS D1.5 (Current Edition) and ASNT TC-1A
17	FDOT would engage NDE firms under contract to the State Materials Office.

Question 8
Does your agency perform NDE inspections with?

Answer Options	Response Percent	Response Count
a) In-house personnel	20.0%	4
b) Consultants	5.0%	1
c) Both	75.0%	15
	answered question	20
	skipped question	11

Question 9
What determines whether in-house or consultant NDE is used?

Answer Options	Response Percent	Response Count
Scope of the project	20.0%	3
Type of NDE testing performed	66.7%	10
Other (See Below)	13.3%	2
	answered question	15
	skipped question	16

Responses	Other (please specify)
1	Both scope and type of testing.
2	Time, type of testing and access required are all factors in determining who and what is required.

Question 10
Does your agency have certification/education/experience requirements for personnel (NDE contractors/consultants or in-house personnel) performing NDE work on your bridges?

Answer Options	Response Percent	Response Count
Yes	60.0%	12
No	40.0%	8
If Yes, please list those requirements (See Below)		11
	answered question	20
	skipped question	11

Responses	If Yes, please list those requirements
1	SNT-TC-1A and in-house procedures
2	Per SNT-TC-1A
3	Contract specific. We have required Level III technicians for UT and PAUT testing. AE testing has been performed through research.

4	ASNT, SNT-TC-1A, Supplement C Level II Certification or higher and experience with performing this work specifically in bridge applications
5	5 years direct experience required for our contracts with consultants, current CWI.
6	NDOT Qualification and Certification for NDT
7	In-house personnel trained to ASNT level 1 or 2, consultants certified ASNT level 2
8	Required to take NDE NHI courses and some outside courses required.
9	In house personnel are to have experience with dye penetrant testing and mag particle testing. Ultrasonic testing of pins, etc. is consulted out to certified professional.
10	ANSI/ANST CP-189-2011 (Level II) AND/OR NHI 130078 Fracture Critical Inspection Techniques
11	NDE contractors must be approved by the State Materials Office.

Question 11
In the preparation and use of NDE, Who:

a) Determines the required NDE methods?		
Answer Options	**Response Percent**	**Response Count**
In-House Personnel	55.0%	11
Consultants	0.0%	0
Both	45.0%	9
	answered question	**20**
	skipped question	**11**

b) Performs the NDE testing?		
Answer Options	**Response Percent**	**Response Count**
In-House Personnel	20.0%	4
Consultants	5.0%	1
Both	75.0%	15
	answered question	20
	skipped question	11

c) Interprets the NDE results?		
Answer Options	**Response Percent**	**Response Count**
In-House	20.0%	4
Consultants	0.0%	0
Both	80.0%	16
	answered question	20
	skipped question	11

d) Determines the importance/impact of the NDE findings in terms of need for follow-on bridge actions (e.g. closure, repair, replacement or do nothing)?		
Answer Options	**Response Percent**	**Response Count**
In-House	45.0%	9
Consultants	0.0%	0
Both	55.0%	11
	answered question	20
	skipped question	11

Question 12
Provide descriptions of routine and major NDE work/projects performed over the past 5 years.

a) When do you perform routine NDE work?		
Answer Options	**Response Percent**	**Response Count**
Biennial Inspections	10.5%	2
Annual Fracture Critical Inspections	5.3%	1
Both	21.1%	4
Other (please specify)	63.2%	12
	answered question	19
	skipped question	12

Number	Other (please specify)

1	Biennial Fracture Critical Inspections
2	Biennial Fracture Critical inspections
3	Annual Inspections and Fracture Critical Inspections as needed when the visual inspection indicates noteworthy changes affecting maintenance forces response and public safety.
4	As determined during the inspections.
5	After visual indication for verification of cracking. Fracture critical inspection of pin and hangers. In-depth inspections of complex structures.
6	Routine NDE work is used for Pin inspections, other non-routine NDE work as identified by the bridge inspectors.
7	On-call to determine if existing steel bridges are repairable or good candidates for rehabilitation.
8	We test pins in pin & hanger assemblies every 5 years.
9	EVERY 6 MONTHS OR EVERY TWO YEARS
10	Special Inspections
11	On FC Inspections when considering a Condition State 4. Some completed on the biennial inspection but very limited. Normally condition found and a special inspection is scheduled from findings.
12	When deemed needed.

b) In describing major (non-routine) NDE projects explain what work was performed, when (what year), by whom and what issue was addressed for example: “The DOT used an NDE firm to perform ultrasonic testing on all of the tie-chord butt welds of a major tied-arch bridge over the Mississippi River due to cracking problems (2009)"	
Answer Options	Response Count
	14
answered question	14
skipped question	17

Number	Response Text
1	Ultrasonic thickness testing of all gusset plates in the state following the 35W bridge collapse in 2007.
2	In depth ultrasonic corrosion survey of the Stillwater Lift Bridge in 2012 by in-hour personnel.
3	DOT used AE to listen for cracking during ongoing rehab of Toledo's Anthony Wayne suspension bridge. DOT sampled a small number of places on the cable to remove sheathing and visually inspect for corrosion, section loss and brakes. The crack locations, none were discovered, would then be additional locations for sheath removal and in-depth inspection (Research Project with University of Toledo and Mistras, 2014-current). DOT used forced vibration testing on 8 stay-cables in order to estimate the tension forces using frequency measurements. This information was used to correlate with pull-off tests of strands (Consultant Motioneering 2014). IR obtained at highway speeds (2015) to determine element quantities and delams. IR used on underside of bridges over traffic in order to determine loose delams at risk of falling (Pooled-fund research with 14 states lead by University of Missouri). IR camera is operated by in-house staff. SHM embedded within Cable Stayed structures during construction to better understand loads and their load-transfer (2006, 2008 US Grant, 2016 Ironton Russell).
4	INDOT used an NDE firm to perform UT and RT tie-cord butt welds on I-64 over the Ohio River in 2011.

Number	Response Text
5	Varina Enon Bridge, I-295 over James River. Borescoped 540 anchors out of 1000 anchors inspected - 2004. Magnetic Flux Leakage Testing - External post-tensioned tendons, PT tendon Corrosion and failure of one tendon, January 2008. Stay Cable System: 2007 In-depth inspection - used Wichitech RD Tap-Hammer and infrared thermographic images for stay inspection. 2007 & 2012 In-depth inspection - used accelerometer for Stay Cable Force Measurement. Bridge Load Testing with IBIS-S Interferometric Radar System, Spans 5 & 6 September 2012. Main Magnetic Flux Method (MMFM) by Tokyo Rope on 11 external tendons - June 2015. I-64 over Maury River, Steel delta frame, Evaluation of Fatigue-Prone Details using Low-Cost Thermoelastic Stress Analysis (TSA), using micro bolometer thermal imager and dedicated field computer - 2014. Hampton Road Bridge-Tunnel, I-64 approach spans - 2010 - "assess completely the condition of the jacketed piles. However, a combination of half-cell measurements, sonic echo, impulse response, and chloride analysis was useful in evaluating the condition of jacketed piles. Ultrasonic pulse velocity was used to determine the velocity of sound through the piles, which was used in the calculations for sonic echo, impulse response, and cross-hole sonic logging. Resistivity measurements were used to evaluate the susceptibility of the concrete and mortar to corrosion. Ground-penetrating radar was ineffective in determining the condition of the underlying pile while the jacket was intact because of signal reflection and attenuation caused by steel mesh reinforcement in the mortar. Cross-hole sonic logging was not a practical evaluation method for this application because of the difficulty in placing the transducers on the piles. " Coleman Bridge - Magnetic Particle Testing of interior and exterior fillet Welds of Pivot Box Girders - Evaluated three different times for hydrogen induced cracking. December 3, 2013 was the second consecutive inspection with no defects indicated which met the criteria for concluding the magnetic particle testing of the girders for hydrogen induced weld cracking.
7	Confirm the presence and/or length of crack in a coped or cut-short flange of floor beams and stringers. Confirm the presence and/or length of crack in the connection of an internal diaphragm to web in a steel tub member. Confirm the presence of a crack at the end of cover plate weld.
8	In 2015, the NMDOT used an NDE firm (JD Inspection Inc.) to perform ultrasonic testing and magnetic particle testing on a steel plate girder bridge over US 84/285 in Santa Fe, NM to determine if the girders were salvageable for rehabilitation (re-deck) or needed to be replaced (superstructure replacement).
9	We use NDT to inspect pins in pin & hanger assemblies every 5 years. Everything else is on an as needed basis.
10	CONSULTANTS USED TO DO ACCESS INSPECTION (2-YEAR INTERVAL) OF CALLAGHAN/TILLMAN OVER COLORADO RIVER.
11	A consultant hired by MDOT used magnetic particle testing to quantify out of plane bending fatigue cracks on several high traffic bridges in Jackson, MS (2008-2014).
12	The DOT used a NDE firm to perform ultrasonic testing of butt welds in girders as outlined in FHWA Technical Advisory 51400.32 issued September, 2011.
13	Wichita post-tensioned box girder bridge analysis, determined the amount of voids in ducts and corrosion potential of strands.
14	After the failure of a Traffic Signal Mast Arm in the Tampa Area an NDE firm was used to perform ultrasonic testing of the connection area of Traffic Signal Mast Arms built under the same contract in that area. Additional problems were found.

Question 13
Provide cost information for performing NDE on bridges.

a) What is your estimate annual NDE cost for routine inspections?	
Answer Options	Response Count
	15
answered question	15
skipped question	16

Number	Response Text
1	Cannot be determined.
2	Nominal
3	Not readily available.
4	Not available
5	$150,000 every 5 years for routine pin inspections.
6	This information is not readily available.
7	U/T work for pin-hanger connections is ~200-250/each pin-hanger connection. Dye-penetrant or mag particle testing to identify cracks is ~50-100 per crack.
8	20000
9	N/A
10	DON`T KNOW
11	100000
12	Unknown - routine testing is performed as part of regular inspections and the costs are not tracked separately.
13	Not often done on routine inspections so just part of doing daily business.
14	For routine inspections with in house staff probably about $5,000 (mostly materials, not counting depreciation of equipment). For routine inspections by consultants around $50,000 per year.
15	For routine inspections, only Dye Penetrant and Magnetic Particle would be used by the inspectors when indications were found. No additional funds are provided to the consultant inspectors so no cost data is available.

b) For major (non-routine) NDE work, provide quantities (if possible) and project costs for NDE work (include access, incidental and traffic control expenses if broken out) for example: "For the Mississippi River tied arch bridge inspected in 2009, the DOT's cost for ultrasonic testing of butt welds was $1,980,000 for inspecting 200 locations. The access cost was $270,000. The cost for lead

paint removal and repainting was $100,000. The traffic control cost was $300,000 and the NDE cost was $1,310,000."	
Answer Options	Response Count
	12
answered question	12
skipped question	19

Number	Response Text
1	Cannot be determined.
2	Not readily available.
3	NDE was used on two bridges on I-70 near Eagle-Vail to evaluate all fatigue locations for a retro fit project. Unfortunately, specific quantity and cost information is not readily available.
4	For the cable stayed Mississippi River bridge the total contract cost for NDE evaluation of the cable stays was $1,164,000.
5	Impact Echo for ~ 500,000 square feet of concrete deck area along the interstate was $430,000.
6	For the 80' single span Bridge over US 84/285 inspected in 2015, the NMDOT's cost for ultrasonic testing of welds was $11,000 for inspecting approximately 50 locations. The access cost and traffic control cost was $3,000 and the NDE cost was $8,000."
7	N/A
8	Not available
9	The costs for UT testing of butt welds following FHWA Technical Advisory 51400.32 was $14,000. Traffic control and access equipment costs are not included.
10	Wichita post-tensioned box girder bridge analysis, Almost $1 M when completed plus another $5 M in Design and Construction Repair Project.
11	None.
12	Not available.

Question 14
How are NDE results used for bridge decision-making by your agency? (e.g. During our district office personnel's visual inspection they may perform Magnetic Particle (MT) and Dye Penetrant Testing (PT). If an anomaly is found a consultant will be hired to perform Ultrasonic Testing (UT) to further identify the anomaly. Central Office will review the findings and make recommendations for plan of action.)

Answer Options	Response Count
	18
answered question	18
skipped question	13

Number	Response Text
1	All inspection reports are reviewed by Bridge Office engineers and if problems are found repair recommendations are made.
2	DOT uses NDE for refining material costs at the scoping stage, comparing NDE with destructive testing in order to get extent of deficiencies, locating tips of cracking in steel in order to know where to drill-stop the ends, understanding loads in a cable-stay structure.
3	Based on specialty details or specific findings.
4	The Districts evaluate the NDE results and make recommendations for plan of actions with recommendations from Virginia Transportation Research Council (VTRC) and Central Office Structure and Bridge or have a consultant to develop plan of action and repair plans.
5	If District personnel has an issue that they are not sure about they will contact Central Office and we provide guidance and/or we go look at it ourselves.
6	NDE results are used by the Bridge Inspections Unit for make repair recommendations to the Regions.
7	Visual inspections and bridge type will determine the need for NDE for a specific bridge. The NDE results will be forwarded to Central Bridge Office staff who will make the final determinations of what actions to take.
8	Used by in-house Bridge Inspection Engineer and Bridge Management Engineer to confirm the BrM element rating and NBI Condition Rating. Also aids in determining the urgency of the defect and the path forward to having the defect corrected/repairs (if necessary). Some defects may just be monitored.
9	For the Bridge over US 84/285, the results compiled by the NDT consultant were used to determine if the welds and girders are repairable. It was determined from the results that the steel girders were salvageable and the Bridge will be re-decked with weld repairs and grinding made to the existing girders.
Number	Response Text
10	NDT for pins is used to determine if a problem exists. Other forms of NDT are used to determine the extents of problems and to estimate for repairs.
11	Structures Division will review the findings and make recommendations for plan of action.
12	If we find a suspect area, NDE is used. Depending on results action may be taken. NDE may be used for this as well such as finding the end of a crack for drilling.
13	The information is generally used to quantify how much repair work will have to be performed. For example, MDOT used the results of the GPR and infrared bridge deck scanning to estimate how much of the bridge deck will have to be repaired full depth, how much of the deck is delaminated, etc.

14	Anomalies for during inspections are tested using MT testing by the inspector. Central Office engineering staff will review the findings and determine appropriate actions, including further testing or remedial measures.
15	Used to determine corrective actions and inspection requirements and cycles along with making replacement/rehab decisions.
16	During typical biennial inspections, TDOT bridge inspectors may perform dye penetrant or mag particle testing on a suspect crack area. If crack is confirmed through this testing, the finding is reported the bridge evaluation office (central office) to assess and make recommendation for a plan of action.
17	The inspectors perform mag particle or dye penetrant testing on areas prone to fatigue cracking and for crack monitoring for areas that have experienced issues. Decisions are made by the maintenance engineer regarding potential work activities or for reduced inspection schedules. UT inspections performed by consultants are used in much the same way for monitoring pin and hanger conditions.
18	If additional NDE is needed, the results would be interpreted by the district with the State Material Office and Central Office being available as resources. Action would be decided by the District.

Question 15
Has your agency used NDE in conjunction with structural health monitoring/bridge instrumentation?

Answer Options	Response Percent	Response Count
Yes	31.6%	6
No	68.4%	13
	answered question	19
	skipped question	12

Question 16
What additional information/training would assist your agency in using NDE on a more widespread basis?

Answer Options	Response Count
	13
answered question	13
skipped question	18

Number	Response Text
1	None
2	INDOT is doing research on how to use NDE in a systematic way to evaluate the bridges.
3	Summary of NDT for different bridge issues (fatigue cracking, corrosion induced cracking steel members, post-tensioning testing for corrosion of internal and external tendons, NDT methods for evaluating corrosion in pre-tensioned prestressing in voided prestressed slabs, boxes, I-girders, and bulb tees and NDT for deck evaluations.) Information on reliability of NDT methods. Training course similar to NHI Course No. 130099, Bridge Inspectors NDE Showcase (BINS).
4	Online classes would be helpful.
5	Other than Dye Penetrant the cost of other NDE methods precludes their widespread use over a very large and diverse bridge inventory.
6	None. We have already had a two day workshop and a training webinar in addition to the Fracture Critical Inspection Course and Bridge Safety Inspection Refresher courses.
7	NOTHING AT THIS TIME
8	none
9	Current national standards/specifications are based primarily on fabrication inspection. It would be beneficial to have guidance for in-service evaluation.
Number	**Response Text**
10	Not sure what is available but we have just recently completed the NHI BINS class and feel we have a reasonable understanding now.

11	I would promote the various NDE testing methods for bridge inspectors. One might set up a one -day training course on each method so that the inspector can become skilled in that test method.
12	More information on the use of instrumentation and monitoring of bridge condition would be helpful. Web based refreshers on the use of mag particle and dye penetrant systems would help.
13	Since anything beyond Magnetic Particle or Dye Penetrant would be done by an NDE contractor we don't see additional training being beneficial.

Question 17

If available, would specialized bridge/highway structure certifications for in-house NDE personnel be implemented in place of existing certifications?

Answer Options	Response Percent	Response Count
Yes	35.3%	6
No	64.7%	11
	answered question	17
	skipped question	14

If Yes, please indicate what changes your agency would want to see		
Answer Options	Response Percent	Response Count
a. Formal NDE introductory training for agency personnel: Y/N if Y list what methods need to be addressed by technical courses.	33.3%	2
b. Moderate experience requirements for qualification.	33.3%	2
c. Some training focused on typical bridge problems.	66.7%	4
d. Applied training using actual bridge defects.	100.0%	6
e. An NDE training/certification program for agency bridge personnel.	83.3%	5
f. Executive course for NDE managers.	33.3%	2
	answered question	6
	skipped question	25