

NDE for Steel Bridges: UT, MT, PT and Eddy Current

Visual inspection is the backbone of steel bridge inspection, but it finds only flaws large and pronounced enough to see. This course explains the nondestructive evaluation (NDE) methods used on in-service steel bridges: dye penetrant (PT), magnetic particle (MT) and eddy current (ET) for surface flaws; ultrasonic testing (UT), including straight beam, angle beam, thickness gaging and phased array, and radiography (RT) for internal flaws; and acoustic emission (AET) for crack activity. It covers how each works, what it can and cannot find, how to choose methods by flaw type and location, how flaws are confirmed, sized and characterized, and how NDE findings feed engineering decisions. It is built on the Kentucky Transportation Center's 2016 report *Nondestructive Evaluation of Steel Bridges: Methods and Applications*.

Learning objectives

- Describe visual, PT and MT
- Explain UT for welds and pins
- Use eddy current
- Choose methods by flaw type

Why steel bridges need NDE

The Kentucky Transportation Center's 2016 report *Nondestructive Evaluation of Steel Bridges: Methods and Applications* (Hopwood, Goff, Fairchild and Palle, KTC-16-26), prepared with the Kentucky Transportation Cabinet and FHWA, frames the problem with Kentucky's own inventory: about 1,050 steel bridges with an average age of 47 years, almost equal to their 50-year design life. As bridges age, the report notes, the cumulative effects of loading, environment and service practices such as deferred maintenance and deicing chemicals progressively deteriorate structural steel. In some cases, design, material, fabrication or construction problems interact with service deterioration to make it worse.

The report defines NDE as an important tool that helps transportation departments address problems that threaten the structural integrity of steel bridges, and lists its uses: assessing indications found by other methods, searching for potential flaws, flaw detection, flaw characterization and flaw sizing.

Where the problems come from. Excluding corrosion, the report traces many steel bridge problems to the emergence of welding, which introduced the possibility of weld defects that replicate cracks and short-circuit service life. It lists primary design problems as abrupt section changes, re-entrant corners, poor weld designs affecting residual stresses and fracture behavior, lamellar tearing, and overuse of nonredundant designs. Riveted bridges have also experienced cracking, typically after years of service.

Steels. Bridge steels were proprietary until 1901, when ASTM A7 was issued. The report lists common bridge steels as low-carbon (A7, A373, A36), high-strength low-alloy (A242, A441, A572, A588 and A709 grades 50 and 50W) and high-strength quenched-and-tempered steels (US Steel T-1, A514, A517 and higher A709 grades). Kentucky had used only A709 grade 50W for about the previous ten years. The report notes that several high-yield quenched-and-tempered bridges experienced significant weld cracking, a recurring theme in the case histories in this course.

Mill and fabrication flaws. Steel may contain surface defects (scabs, slivers, laps and seams) and subsurface flaws (stringers, inclusions and porosity). Inclusions flattened by rolling form planar laminations that can cause tearing in some weldment

designs. Fabrication can introduce notches from poor fit-up, slag inclusions, porosity, cracks, lack of fusion and lack of penetration. Shops have quality control NDE personnel, and owners have quality assurance personnel who review shop NDE results. This course concerns NDE of in-service bridges, though the same methods are used in the shop.

The role of NDE in decisions. The report stresses that NDE is only part of a decision process. Regardless of method, some supervisory decision making is ultimately required, leading either to follow-up action (repairs, load restrictions, further inspections) or elimination of the concern. Even a no-action result has value, because testing reduces risk. No test is perfect, but the most appropriate methods, properly applied and interpreted, reduce residual risk to a low level. Where NDE shows no current flaws, periodic retesting may be scheduled to catch fatigue cracks too small to detect initially. And the report is explicit that the interface between the NDE operator and the engineer making decisions is critical.

This course follows the report's structure: the flaws to be found, the surface methods, the internal methods, acoustic emission, and then the use of NDE in inspection and decision making. Fatigue details are covered in BR-F01, nonredundant steel tension members in BR-F02, and steel superstructure inspection generally in BR-I07.

Steel bridge damage and the flaws NDE looks for

Five kinds of problems. The KTC report says steel bridges can have problems manifested as corrosion, cracking, wear, distortion or surface blemishes, alone or in combination, each with root causes. A simple repair such as drilling a check hole may stop a crack, but in all likelihood the root cause should be addressed to resolve concerns at similar sites on the same bridge and others.

Corrosion. The report calls general corrosion probably the most common problem on steel bridges today. Deck runoff and traffic aerosols containing deicing salts exacerbate it. Section loss raises dead and live load stresses and creates stress concentrators that may lead to cracking. Corrosion can also freeze pins and hangers in pin-and-hanger connections, causing them to fracture. Corrosion cracking is relatively infrequent, but corrosion fatigue can occur in members immersed for long periods, and high-strength steels and wires (suspension cables, hangers, prestressing and post-tensioning strand) are particularly vulnerable to stress corrosion.

Cracking. Cracks typically occur at joints, connections and geometric discontinuities, and are commonly oriented transverse to tensile stress, though they can also run parallel (tearing or out-of-plane cracking). Some cracks are benign, usually from manufacturing or fabrication, yet can look alarming and require significant investigation to demonstrate they are not a threat. More serious problems arise when cracks grow by fatigue, stress corrosion or corrosion fatigue. These are sub-critical crack growth mechanisms: the crack does not cause failure until it reaches a critical size, at which point the component typically experiences unstable fast fracture.

Critical crack size. The report explains that critical crack size depends on the magnitude and orientation of live, dead and residual stresses, steel toughness at minimum service temperature, component thickness and detailing. In many cases critical sizes are large enough that cracks can be detected visually or by NDE well before fracture. But in a limited number of cases, no sub-critical crack exists before fast fracture, or it is too small to detect reliably. **In those cases, remedial action is required in lieu of NDE.** The Hoan Bridge is the report's example: a weld attachment detail and three-girder layout led to near collapse; there was no physical flaw before the crack formed and ran brittly through two girders, so no NDE method was practical.

Welds and rivets. Welding is a common source of cracking, transverse to or along welds. Shop QC/QA is usually effective, but some early welded bridges, especially with quenched-and-tempered steel, had many weld cracks in fracture critical

members; the report cites the I-65 John F. Kennedy Memorial Bridge (early 1990s) and the I-64 Sherman Minton Bridge (2011). Welded members are monolithic, so an unstable crack can sever the whole component. Riveted members, built from plates and angles, have lower fatigue resistance than bolted ones but may be more resistant to complete failure because a crack in one piece does not automatically run into the next. Fatigue cracks in riveted members run from under rivet heads, transverse to stress.

Wear and distortion. Fretting can make one component cut into another, such as a plate into a pin, and wear can elongate pin holes. The report notes the estimate that 90% of fatigue-related cracks in bridges arise from out-of-plane distortion near connections between girders and out-of-plane elements, and that pack rust between faying surfaces of built-up riveted members also causes distortion.

Surface blemishes. Slivers, scabs, arc strikes, dents and gouges can mostly be ignored, but some, such as arc strikes, can be problematic and need periodic inspection or repair.

Flaw classification. For NDE, flaws are external (surface) or internal (subsurface), and planar (cracks, lack of penetration, lack of fusion, laminations) or volumetric (porosity, slag). Surface-breaking planar flaws appear as linear indications. Volumetric flaws are typically internal. These classifications drive method selection.

Visual inspection, operators and the indication-flaw-defect chain

Visual testing. The KTC report identifies visual inspection or visual testing (VT) as the NDE method most widely used by inspectors for all bridge materials. Its limitation is that it finds only surface flaws pronounced enough to be noticed, by an inspector who may be simultaneously rating elements, dealing with traffic or working at height, often in marginal lighting. Proper access and lighting are necessary for good visual inspection. The report notes that FCMs in Kentucky were inspected at arm's length annually and redundant members every other year, and that where inspections are not at arm's length, inspectors must know where cracking may occur (fatigue- or fracture-prone details, transverse lateral bracing attachments, skewed structures) and periodically inspect those locations at arm's length from ladders, lifts or under-bridge vehicles.

The 2022 NBIS changed the terminology and interval rules for these members; BR-F02 explains NSTM intervals and hands-on requirements under 23 CFR 650.311 and 650.313.

Operators matter. The report lists physical and psychological attributes of good inspectors: good vision, comfort in the work environment, willingness to do tedious tasks for long periods, technical knowledge of the elements and deterioration mechanisms, and good communication. NDE operators need the same plus specialized knowledge of their methods and equipment, how generic details such as welds are tested, and how indications are interpreted. Some operators lack bridge experience and need help from knowledgeable inspectors or engineers. Some methods require minimal equipment and knowledge and are commonly used by inspectors; others require trained specialists. The report emphasizes that operator factors significantly influence results, and describes a major bridge NDE project in which ultrasonic operators had to find flaws in test plates in the actual bridge environment to confirm the surroundings did not impair their performance.

Indication, flaw, defect. The report draws a careful chain of terms. An NDE method gives the operator an *indication*: a location where the response differs from the bulk material. The operator interprets whether the indication is relevant, whether it is a *flaw*, what type, and whether it constitutes a *defect*. The last judgment may lie outside the operator's expertise and authority. A flaw is a defect when it falls outside specifications or is expected to cause failure in service.

Two kinds of error. The report describes Type 1 errors, where the operator misses a flaw or does not interpret an indication as a flaw (an *undercall*), and Type 2 errors, where the operator misinterprets an anomalous indication as a flaw (an *overcall*).

Type 1 errors are reduced by choosing the proper method and by operator skill. Type 2 errors are addressed by using a different operator or method to confirm or discount the indication, for example using UT to evaluate an indication found by PT or MT. AE indications must always be verified by a surface or internal method.

Escalation. The report describes a natural escalation: if VT indicates a crack, it is usually evaluated by a surface method (PT, MT or ET). An indication from a surface method is typically evaluated by an internal method (RT or UT, conventional or phased array). An indication from an internal method is usually evaluated by another internal method, or by coring and metallurgical analysis. The Kentucky experience on the I-471 Dan Beard Bridge illustrates the value of confirmation: after tie-chord butt weld cracking on another Ohio River bridge, all tie-chord butt welds were tested by UT; a location with a major UT indication was cored, revealing a harmless lamination.

Dye penetrant testing (PT)

The KTC report states that external/surface methods are typically the simplest to apply and easiest to interpret. Steel plates and shapes are of limited thickness, so growing cracks usually break the surface somewhere, and slow growth usually permits timely detection by surface methods before failure. The most common surface method is probably PT, followed by MT and then ET.

Use. PT finds surface-breaking cracks and other surface flaws.

Equipment. Bridge penetrant kits typically contain three aerosol cans: a cleaner, a penetrant and a developer. Fluorescent dyes require a black light. Wire brushes, grinding discs, hammers, scrapers and rags are used for surface preparation; chemical paint removers may be used if the area is properly cleaned afterward.

Surface preparation. Paint and foreign material must be removed from the test area, usually by mechanical stripping of paint, grime and rust, followed by the cleaner to dissolve remaining dirt and films. The report notes that some sources recommend avoiding mechanical coating removal before PT, and that paint strippers contain dangerous solvents or caustics requiring protection.

Procedure. After cleaning, penetrant is sprayed over the surface. It carries a colored pigment, such as red, in a thin oil that flows into surface openings by capillary action. After a holding (dwell) period, excess penetrant is wiped off until none is visible. The developer is then sprayed as a thin film that leaves a white powdery layer, drawing penetrant out of cracks to form a colored indication against the white background. After waiting for the developer to work, the surface is inspected; the indication shows the presence, length and width of the flaw. Fluorescent penetrants follow the same steps but are viewed under black light, giving high contrast in poor light, at night, or in enclosed areas.

Interpretation. The report calls interpretation relatively straightforward: cracks appear as linear continuous or intermittent indications. The inspector records the flaw with a photograph and notes its dimensions and location.

Strengths and limitations. PT is simple and inexpensive, provides initial detection and confirmation of visual findings, and is readily used by inspectors. But the report lists important limits:

- It is slow and may not be cost-effective if more than two or three locations must be evaluated.
- Like VT, it cannot detect subsurface flaws or measure the depth of surface-breaking flaws.
- It is less effective on irregular, rough surfaces.
- Visible dye may not work well in poor light; fluorescent dye may not work in daytime ambient light.

The 2016 survey found PT, followed by MT, was the most common NDE method used by DOTs for routine inspection tasks.

Practical notes. Because PT shows only length at the surface, a PT indication at a weld toe tells the engineer that a crack exists and how long it is on the surface, not how deep it goes or whether it has turned. If depth matters, for example to decide whether grinding can remove the crack, follow-up with UT or ET is needed. PT residue must be cleaned off before repainting, and the report recommends solvent wiping before spot coating, especially after dye penetrant use.

Illustrative scenario. As an illustration only, an inspector notices a rust line at the toe of a transverse stiffener weld on a girder web near the tension flange. PT is applied after removing paint over a few inches. A red linear indication about 1 inch long appears along the weld toe. That confirms a surface-breaking crack and gives its surface length, but whether it extends into the flange, and how deep it is, requires an internal method. The location would be marked, photographed and reported, and crack tips marked and dated.

Magnetic particle testing (MT)

Use. The KTC report states that MT detects surface and near-surface internal flaws in steel and iron components. It requires less careful surface preparation than PT and is faster overall.

Equipment. Permanent magnets or battery or AC-powered yokes; visible or fluorescent iron particles, applied dry with a bulb applicator or wet from aerosol suspension cans; a pie gage (recommended); and a black light for fluorescent particles. Surface preparation tools are the same as for PT.

Surface preparation and coatings. The test area should be clean, dry and free of oil, grease, rust, thick paint and weld spatter. The report states that MT can be used over paint up to 2 mils thick, but because nearly all bridge coatings are three to four times that thickness, best practice is to remove coatings down to bare metal or mill scale. It warns that problems have been observed with MT incorrectly used over thick paint.

Principle. Magnets or energized yokes create a magnetic field between their poles, with lines of flux running through the steel. Any flaw that cuts across the lines of flux creates localized flux leakage, because the flaw cannot carry as much field as the surrounding steel. Leakage is greatest when the flaw is perpendicular to the flux; the report gives 45 degrees as the minimum orientation for reliably generating an indication. That means the yoke legs must be aligned relative to the expected crack direction. If a crack might run in more than one direction, the test must be repeated with the yoke rotated.

Procedure. In dry MT, iron powder is dusted over the area while the field is applied, and excess is lightly blown away; particles cluster at leakage sites to form a visible indication. In wet MT, particles in water or oil suspension are sprayed on and the area magnetized. Particles come in gray, red or fluorescent; a white contrast coating may be applied first. The report describes an AC yoke aligned to detect a crack at the toe of a longitudinal web-to-flange fillet weld on a tie chord, a typical use.

Recording. The inspector photographs the indication and records its size and location. The indication can be lifted with clear tape for a hard-copy record.

AC versus DC. The report notes AC yokes are suitable for surface flaws, while DC yokes can find surface and near-surface flaws. MT is generally considered a poor choice for internal flaw detection and is typically reserved for surface flaws.

Strengths and limitations. MT is relatively simple and requires minimal training, making it ideal for inspectors. It is more cost-effective than PT because it is quicker. But the report notes its use probably needs to be limited to a few sites, especially

where lane closures are required; it can have problems on irregular, rough surfaces; and operators typically do not check field strength or orientation, which the pie gage exists to verify.

Choosing PT or MT. Both find surface cracks and show length, not depth. MT is faster, tolerates slightly less preparation, and can find some near-surface flaws, but it works only on ferromagnetic material and depends on correct field orientation. PT works on any nonporous material and has no orientation dependence, but is slower and needs a cleaner surface. The 2016 survey showed both are the methods DOTs use most often, for routine and condition-specific testing.

Kentucky example. The report notes that UT has been used by KYTC to determine whether a surface indication detected by MT was an actual crack, an example of confirming a surface method finding with an internal method to avoid an overcall.

Eddy current testing (ET)

Use. The KTC report states that ET detects surface and near-surface flaws in steel and iron components.

Equipment. Unlike PT and MT, ET uses no consumables. It requires a portable battery-powered flaw detector with signal generator, controls, sensing circuitry and an impedance-plane screen; lead wires and probes; and reference standards for coatings and crack depth. For typical structural steel, the report recommends a weld probe, a paint probe to measure coating thickness and compensate calibration with shims, and a test block with 2, 1 and 0.5 mm notches. It is a more advanced method than PT or MT and requires operator training and experience.

Surface preparation. Minimal: perhaps removal of stratified rust, weld spatter or heavy debris. The report states ET can be performed over paint films up to 80 mils thick, which is a large practical advantage over PT and MT on coated bridges.

Principle. The instrument drives AC current through a coil in the probe, creating a dynamic magnetic field that induces circular eddy currents in the steel centered on the probe. In steel, penetration is very limited (a skin effect), which restricts ET to surface and near-surface flaws. Flaws transverse to the circular eddy current path disturb the induced field and change the current in the probe, which the instrument detects. Flaws closer to parallel with the eddy currents give reduced indications. Near plate edges, edge effects disturb the field and prevent detection.

The display. The eddy scope's impedance-plane screen shows inductive reactance versus resistance of the coupled probe and test piece. When the probe passes over a flaw, a normally centered dot (pip) deflects. Lifting a conventional single-coil probe off the surface also changes the signal (lift-off effect); specialized weld probes minimize lift-off, do not require removal of paint or tight rust, and can inspect irregular surfaces such as code-acceptable fillet welds. The length of flaw detected is normally considered equivalent to the probe coil diameter, and the report states sensitivity to small surface flaws, cracks down to 0.20 inch in length. Results are real time.

Procedure. Operators must select the right probe and settings and know how to distinguish flaw signals from geometric effects. Per the report, the probe is typically moved in a zig-zag pattern along the heat-affected zone and over the weld bead, then swept linearly along the weld toes. Crack depth can be estimated by comparing signal deflection with reference standards of known depth; crack length by moving along the crack until a specified drop in peak signal. Digital units store screen traces for reporting.

Strengths and limitations. The report calls ET the most cost-effective method for performing multiple tests: surface preparation is minimal, testing is rapid, data can be uploaded for reporting, and it is faster than PT and MT. It suits bridges with many inspection sites, especially where lane closures are disruptive, and can be used with rope access. Limitations: it

needs a skilled operator and proper equipment set-up, and results are affected by surface roughness and variations in material properties. At the time of the report it was an emerging method for bridges.

Why ET matters for fatigue-prone details. Consider, as an illustration, a long-span bridge with hundreds of similar welded connection plate details flagged for fatigue concern. PT or MT at each would require paint removal and repainting at every site, plus lane closures. ET through the coating can screen all of them quickly, with PT, MT or UT reserved for the few locations that give indications. That is exactly the role the report describes: ET for multiple sites, surface methods or UT to confirm.

Ultrasonic testing: principles and straight beam

The KTC report describes internal (subsurface) methods as used to characterize and size indications found by visual or surface methods, to size cracks accurately for fracture assessments and repairs, and to investigate components with limited access (such as pins), questionable welds or weld repairs, and impact damage. These methods are slow and require costly equipment and trained, experienced operators. The two primary internal methods for bridge steel, RT and conventional UT, have different capabilities and can be used to confirm each other.

What UT can find. The report states UT can detect subsurface volumetric flaws such as cluster porosity and slag, and is the best internal method for planar flaws: cracks, lack of penetration, lack of fusion and laminations. It measures thickness for corrosion and construction errors, can find some surface-breaking cracks, and has been used to check whether ends of stay cable strands cracked at anchor blocks.

Equipment. A portable flaw detector with pulser-receiver, controls and display; lead wires; transducers; reference blocks; and couplant (a consumable). Thickness gages are simpler units with a digital readout. The test area must be clean of paint, rust, slag and spatter and relatively smooth.

Principle. The flaw detector sends electrical pulses to a piezoelectric crystal in the transducer, which vibrates and converts them into high-frequency mechanical pulses, typically 2 to 5 MHz for steel. A viscous couplant such as thick oil transmits sound into the steel. Depending on the transducer, the pulses generate compression (longitudinal) waves or shear waves, in which particles oscillate at right angles to the direction of travel. Straight beam transducers produce compression waves; angle beam transducers produce shear waves and can also be designed to produce surface waves. The receiver displays reflections from the near surface, any intervening discontinuities and the back wall.

Calibration and display. For calibrated pulse-echo UT, the instrument and transducer are calibrated on a standard reference block (for example, the IIW block for shear wave testing, or the AWS shear wave distance/sensitivity calibration block). In A-scan mode, one axis shows calibrated amplitude and the other distance along the beam path. Newer digital units provide distance-amplitude correction and AWS reflector indication ratings to help assess severity.

Straight beam scanning. Couplant is spread on the surface and a straight beam transducer moved over it, entirely or on a grid. Intervening peaks between the initial pulse and the back wall may warrant further investigation. Straight beam testing detects flaws parallel to the surface, such as laminations in plate that other methods cannot find, and is typically used on anchor bolts and pins, where sound is sent along the axis to find cracks. It may not be effective for flaws perpendicular to the surface, which is the orientation of most cracks.

Lamination check first. The report notes straight beam scanning is typically done before shear wave testing to find laminations that would block or confuse the angled beam. It adds that preliminary straight beam mapping may show shear

wave UT or PAUT will not be effective because laminations block the sound path, which is more likely in steel that was shop-inspected by radiography rather than UT.

Thickness gages. UT thickness gages use dual-element transducers: one crystal sends a longitudinal wave and the other receives the reflection. From the elapsed time and the speed of sound in steel, the gage calculates and displays thickness. Conventional flaw detectors with dual-element transducers can do the same. The report shows a thickness gage used on a gusset plate and notes these devices measure section loss in components such as gusset plates; the survey found UT often used for section loss measurements on eyebars and gusset plates. Section loss measurements feed directly into load rating of deteriorated members (BR-L04) and gusset plate rating (BR-L05).

Illustrative thickness check. As an illustration only, if a gusset plate detailed at 1/2 inch reads 0.42 inch at the free edge near the deck drain in a grid of readings, that is 16% loss at that location. The pattern of readings, not one number, determines the effective section used in a rating.

Ultrasonic testing: angle beam, phased array and limitations

Shear wave (angle beam) testing. The KTC report describes an angle beam probe as a transducer on a plastic wedge that refracts the sound into the steel as shear waves at an angle, usually 45 to 70 degrees from the normal to the surface. It is usually used to inspect welds. Bouncing the beam off the back wall orients it nearly perpendicular to subsurface weld flaws, improving detection. The operator moves the transducer in a raster pattern at predetermined distances from the weld line. Any flaw of sufficient size gives a distinct reflection along the sound path. Once a significant discontinuity is found, the operator maximizes the reflection amplitude, then determines length by a predefined procedure such as the AWS 6 dB drop method. The transducer position and the flaw location and depth are marked on the steel.

Orientation rule. The report states the general principle for both straight and angle beam testing: detection is best when the beam is normal to the maximum profile of the flaw, and least effective when the beam is parallel to it, especially for planar flaws. Choosing the angle and scanning direction to put the beam across the expected crack plane is the essence of a good UT procedure.

Interpretation. Reflection amplitude relates to flaw size and to distance along the sound path, reflecting attenuation of the outgoing and returning pulses. Calibration on reference standards accounts for distance and sensitivity.

Phased array UT (PAUT). PAUT probes contain many small elements in an array, pulsed in sequence to create constructive interference that forms a beam at a set angle. Changing the timing sweeps the beam through many angles, so the probe can sweep a weld without being manipulated as in conventional shear wave testing. The probe is moved parallel to the weld, sweeping it, which is much faster. An encoder records probe position along the weld for locating flaws. Data are stored digitally and viewed in A-scan, B-scan and sector (S-scan) modes. The report states PAUT provides better imaging and processing, giving better and quicker characterization and sizing, is better at characterizing flaws than conventional shear wave testing, and can map corrosion when one face is intact. Previous research showed PAUT identified fabrication shop defects as accurately as RT or UT. At the time, it was an emerging technology not yet widely used on in-service bridges.

Applications. The report lists UT uses on bridges: confirming surface indications; inspecting plates for cracks or corrosion; detecting cracking in members including pins and fittings; inspecting strands; and accurately locating crack tips before drilling check holes. Accurate tip location matters because a check hole that misses the tip does not arrest the crack. The survey found UT and PAUT commonly used on pins and hangers.

Limitations. UT is generally faster than radiography but may be more time-consuming overall because of coating removal and replacement. Laminations can block the beam. Some UT, especially shear wave testing, requires significant operator knowledge and skill to perform and interpret correctly. The report notes some variability in crack sizing among operators depending on skill and technique, which prequalification procedures may limit.

Sizing. The report states that an internal method such as UT generally provides the most accurate flaw sizing, and that accurate crack sizing is necessary if fracture mechanics is used to judge criticality. It warns that radiography may not be conservative when sizing tight cracks.

Sherman Minton case. The report describes Indiana DOT's 2011 response to tie-chord butt weld cracks on the I-64 Sherman Minton Bridge: UT of a percentage of welds, increased after more flaws were found; discovery of a major crack that led to closure; then RT added and all weld locations tested before the tie chords were repaired. Strain gaging showed the cracks were not under live stresses large enough to cause fatigue; the concern was brittle fracture at low temperatures. The case shows UT used for search, escalation of scope as findings accumulate, and RT used to confirm.

Radiographic testing (RT)

Use. The KTC report states RT detects subsurface volumetric flaws such as porosity and slag inclusions, and, if properly oriented, planar flaws including cracks, lack of penetration and lack of fusion.

Equipment. A radiation source (x-ray tube or radioactive isotope), film cassettes or a digital flat panel detector, image quality indicators (penetrameters) and lead markers; tools for coating removal; and facilities to develop film or download digital images.

Principle. RT detects flaws from differences in absorption of short-wave radiation (x-rays or gamma rays) penetrating the steel. Properly exposed, sound steel absorbs most of the radiation; flaws let more pass, darkening the film. For most bridge work, the report states iridium 192 has been the primary source. The isotope capsule sits in a heavy shielded projector placed on firm support away from the test location. A guide tube runs to the test location, and the operator cranks a control cable to push the source pellet to the end of the tube (the snout) for the exposure, then retracts it.

Image quality. Film in a light-tight cassette is placed on the far side of the part. A penetrometer, a strip with holes or a set of wires of varying diameters, is placed on the source side to confirm image sensitivity, usually set at 2% of the test piece thickness. Lead letters, numbers and arrows identify the image. Digital radiography uses flat panel sensors read in a lab, producing an image on a computer without film development and allowing manipulation and direct inclusion in reports.

Interpretation. A technician proficient in industrial radiography interprets the image, relates discontinuities to specific flaw types (characterization) and sizes them. The report notes that subsurface flaws are best characterized by type using radiography, and that the combination of size and type is used to judge criticality.

Limitations and hazards. The report lists:

- A radiation hazard requiring care; test areas must be cordoned off and placarded.
- Post-processing delays evaluation; large programs may bring a portable lab to the field.
- Welds may need multiple shots to detect planar flaws at one location.
- Lead paint may inhibit RT and require removal; irregular weld surfaces may need grinding for contrast.
- RT cannot detect planar defects unless the source is properly aligned with them, so it cannot detect rolling laminations in plate.

- It locates internal flaws in plan relative to the film but cannot give their depth.
- It is probably the most expensive NDE method to use in the field.

Strengths. RT provides a good permanent picture of indications and dependable interpretation of flaw type, which helps decisions about the need for and extent of repairs. The report notes it may eliminate the need to remove and replace paint, a significant expense, and can be used to verify other methods. In some cases it offers critical information about severity.

UT and RT as complements. The two primary internal methods have mirror-image strengths: UT is best for planar flaws such as cracks and lack of fusion, gives depth, and can find laminations; RT is best for volumetric flaws and flaw-type characterization, gives a permanent image, but misses misaligned planar flaws and gives no depth. When the consequence of a wrong call is high, as on the Sherman Minton tie chords, both may be used.

Acoustic emission testing (AET)

Use. The KTC report states AET detects activity in known cracks that indicates sub-critical growth from fatigue, stress corrosion or corrosion cracking. It can detect nucleating or growing cracks where they are not readily accessible or are too small to observe. Unlike other methods, AET responds to flaw activity, which the report notes can be considered a measure of severity.

Principle. Steel undergoing loading, weld heating and cooling, or corrosion releases elastic energy that can be detected much as seismographs detect earthquakes. Sources in steel include localized plasticity at a crack tip, corrosion product fretting in cracks, and fracturing of nonmetallic inclusions in high-stress areas. Emissions radiate from crack tips as transient elastic waves lasting microseconds. Sensors similar to UT transducers, operating above 100 kHz and immune to audible noise, are coupled to the steel (paint removed at attachment sites) and held by magnetic hold-downs. Preamplifiers boost the weak signals to a multichannel AE monitor with a common time base.

Noise. The report emphasizes that bridges are noisy: rubbing fasteners and faying plates, loose deck joints, electrical noise from vehicles and power lines, and fretting between deck and beams can mimic emissions, and noise events can exceed valid events by several thousand to one. Systems use sensor arrays and signal processing to reject noise.

Arrays. For a known or suspected flaw, a single active sensor near the flaw can be surrounded by guard sensors so that only signals reaching the active sensor first are accepted. A linear array of two sensors at known spacing locates activity along the line between them from the arrival-time difference, accepting only events whose time difference is less than the travel time between sensors. Planar arrays of three or more sensors triangulate locations but are used infrequently on bridges. A mechanical pencil lead break or an ultrasonic pulser simulates emissions to check the array's location function.

Loading and duration. Bridge AET requires structural loading. Normal traffic can generate activity in a few hours for very active sources; proof-type truck loads can also be used. A knowledgeable operator must design the array, settings, loading and duration. Long-term monitoring needs weatherproof enclosures and power. AE data can be coupled to strain gages to correlate activity with load, and to alarms for continuous monitoring.

Applications. The report lists plates, rolled shapes, pins, cable fittings and wires; monitoring existing cracks or suspect locations such as questionable weld repairs; evaluating retrofits to determine quickly whether they arrested crack growth (citing an evaluation of retrofits on the I-80 Bryte Bend Bridge in Sacramento); and monitoring locations where frequent conventional NDE is impractical (eyebars) or impossible (stay cables).

Limitations. AET does not geometrically define flaws, though it locates them relative to the array; conventional NDE may be needed to size and repair them. It can produce false calls if noise rejection is defeated, which an expert operator minimizes. AE indications must be verified by a surface or internal method.

Structural health monitoring. The report describes SHM as permanent or long-term sensors (stress, strain, deflection, vibration and AE) linked to data acquisition and telemetry, with alarms to agency staff. Where known cracks exist, electrochemical sensors, crack growth gages and AET determine whether they are growing. In the survey, 31.6% of DOTs used NDE as part of SHM, likely mostly AE. The report suggests SHM where risks would require frequent conventional NDE that is prohibitively expensive.

Other methods. The report mentions hardness testing (ultrasonic, rebound and impact) to confirm proper steel; magnetic flux leakage for stay cables; electrochemical crack growth sensors; sounding of rivet heads to find broken rivets; crack propagation gages; and 3D scanning of irregular corrosion loss on gusset plates. On the I-275 Combs-Hehl bridges, hardness testing was used to find improperly heat-treated A514 plates that cracked from the interior face, where cracks could not be seen until they were through-thickness.

Choosing methods by flaw type, location and purpose

Five purposes. The KTC report groups NDE applications as evaluating indications from other methods, searching for potential flaws, detecting flaws, sizing flaws and characterizing flaws. Each purpose points to different methods.

Selection by flaw and location. Drawing the report's method descriptions together:

- *Surface-breaking crack at an accessible weld toe or base metal:* PT or MT to confirm and measure length; ET where many sites or coatings make PT/MT costly.
- *Crack depth, or whether a crack has turned or extends into an adjacent plate:* UT (angle beam or PAUT), or ET against depth standards for shallow cracks.
- *Internal planar weld flaws (lack of fusion, lack of penetration, cracks):* UT is the best internal method; RT if properly aligned.
- *Internal volumetric flaws (porosity, slag) and flaw type characterization:* RT.
- *Laminations in plate:* straight beam UT; RT cannot find them.
- *Pins and anchor bolts:* straight beam UT along the axis; PAUT. The survey found UT and PAUT commonly used on pins and hangers.
- *Section loss on gusset plates and eyebars:* UT thickness gage; PAUT corrosion mapping; 3D scanning for irregular surfaces.
- *Whether a known crack or retrofit is active:* AET, with strain gaging.
- *Inaccessible components (stay cables):* AET, magnetic flux leakage.

When to search. The report lists circumstances that justify searching where no indication exists, including where cracking has occurred at similar locations or on bridges with similar details, components that cannot be inspected visually, suspect construction practices, members subjected to significant overloads, and evaluation of field welding or repairs and retrofits. It notes fatigue cracks are typically present for only about the last 10 percent of the stress cycles leading to fracture, so searching fatigue-prone details is meaningful only if done with appropriate methods and frequency.

Case histories that drove searches. The report recounts the US 18 Marquette-Joliet Bridge, built in 1975, with tie-chord cracks soon after due to defective (banded) A441 steel; the I-79 Neville Island Back Channel Bridge near Pittsburgh, closed

months after opening due to cracks in electrosag welds, one nearly severing a deep girder, with welds of low toughness and large grain size that made UT difficult; the I-24 Paducah bridge tie-chord butt weld cracks in 1975, later lapped with splice plates, which prompted UT of all tie-chord butt welds on the I-471 Dan Beard Bridge; and the 2008 discovery of a cracked splice plate during hardness testing on the Combs-Hehl twin bridges, prompting UT of similar splice plates on all four trusses.

What DOTs actually do. The 2016 survey (31 responding DOTs) found over half routinely use NDE on steel bridges, most often on fracture critical bridges; PT then MT are most common for routine tasks; all seven candidate methods (PT, MT, ET, UT, PAUT, RT, AET) are used for condition-specific testing; UT is often used for section loss on eyebars and gussets; AET and UT on post-tensioning and stay cable strands. Agencies adopt AWS D1.5 for welded components, ASTM standards for specific tests, NHI fracture critical guidance and ASNT documents for personnel qualification. About 75% use a mix of contract and in-house staff; 60% have qualification requirements for NDE personnel, including ASNT SNT-TC-1A and NHI training.

Illustrative selection. For illustration only: a cover plate end on a two-girder bridge tension flange shows a rust stain. ET through the paint screens the detail and similar ones along the span. At the indicating location, MT confirms a surface crack and length. Angle beam UT sizes depth and checks whether it has entered the flange. Those results go to the engineer for a criticality decision and repair design.

From finding to decision

Locate, record, mark. The KTC report states that once a flaw is detected, it must be located and sized accurately. If repairs are not immediate, the location must be recorded for follow-up: measurements, photographs, marking the component, and a sketch showing location, size and orientation. Where fatigue is a concern, tips of surface-breaking cracks can be marked with a punch or indelible ink and dated, so later inspections can tell whether the crack has grown. The report recommends paint pens where marks must last years outdoors, magnetic rulers for photo scale, and flashlights and 10x magnifiers for PT and MT.

Flaw severity. The report ranks flaw severity, from worst to least, as cracks, lack of fusion, lack of penetration, arc strikes, slag stringers and porosity, neglecting stress concentrations from fabrication, corrosion or damage. Non-crack flaws are typically judged by their propensity to generate fatigue cracks. It notes it is generally easier to characterize severity by size than by type, and that cracks transverse to principal tension in fracture critical members growing by fatigue are probably the most common critical circumstance on steel bridges.

Three ways to judge criticality.

- *Workmanship standards* such as AWS D1.5. The report calls these generally conservative for in-service bridges; much larger flaws can sometimes be tolerated.
- *Fracture mechanics*, which calculates whether a flaw of a given size in a given stress field and toughness can fail unstably. Widely used in other industries, its bridge use has been limited. The report notes cracks much larger than predicted critical sizes have been found in service, such as a crack 22-1/2 inches long by 3/8 inch deep in a high-strength steel girder on the I-65 Kennedy Bridge reported in 1991, while very small cracks have caused brittle fractures when not all factors were known. The Fracture Analysis Diagram relates stress and critical crack size to temperature relative to the nil-ductility temperature.
- *Agency policy*, for example requiring repair of all cracks or certain types, with time limits between detection and repair.

Immediate actions. The report gives two contrasting examples. On the Sherman Minton Bridge, the route was shut down immediately when fracture mechanics indicated a cracked tie chord was at risk. On one of the I-275 Combs-Hehl bridges, a crack led to immediate posting at 6,000 lb with trucks diverted, without fracture analysis, until defective splice plates were replaced. Under the current NBIS, findings like these are also critical findings with reporting requirements; BR-I03 covers that process.

Damage tolerance. The report notes that DOTs have tolerated some flaws, such as out-of-plane bending cracks in floor beams of tied arch bridges, and even cracks in girder tension zones when not thought to be growing fatigue cracks. That is a judgment for the engineer, supported by NDE sizing and, where appropriate, AE monitoring.

A five-step process. The report proposes: (1) identify a problem or concern, including a flaw found at similar locations or on similar bridges, even in other states; (2) determine effective methods and qualified personnel; (3) apply NDE promptly; (4) interpret the findings; and (5) develop remedial action if warranted. A key early question is whether the concern is isolated, such as an impact to one girder, or affects similar locations across the bridge. Metallurgical analysis may be needed.

Safety and coatings. The report identifies coating removal as the primary hazard besides working at height: orange or red primers should be suspected of containing lead, dust requires respiratory protection, and removed lead paint must be captured and disposed of properly. Disturbed areas should be repainted, with a direct-to-metal acrylic recommended for spot repairs, applied dry, mid-day, with no rain forecast for 24 hours.

Recommendation in brief. NDE is not a substitute for good details, good fabrication or engineering judgment. Where a detail can fail with no detectable sub-critical crack, retrofit rather than NDE is the answer. Where cracks grow slowly, the right method, applied by a qualified operator, confirmed by a second method when stakes are high, and interpreted jointly with the engineer, turns an uncertain indication into a defensible decision.

Key takeaways

- PT, MT and ET find surface and near-surface flaws; UT and RT find internal flaws; AET detects active crack growth.
- MT needs coating removal (usable over only about 2 mils of paint per the KTC report) and correct field orientation; ET works through coatings up to about 80 mils and suits many sites.
- UT is the best internal method for planar flaws such as cracks and lack of fusion and gives the most accurate sizing; RT is best for volumetric flaws and flaw type but misses misaligned planar flaws and gives no depth.
- Confirm indications with a second method or operator to avoid overcalls; AE indications must always be verified.
- Where a detail can fracture with no detectable sub-critical crack, remediation, not NDE, is required.

References

1. Hopwood, T., II, Goff, C., Fairchild, J., and Palle, S., Nondestructive Evaluation of Steel Bridges: Methods and Applications, Research Report KTC-16-26/SPR15-505-1F, Kentucky Transportation Center, University of Kentucky, 2016 (doi:10.13023/ktc.rr.2016.26)

Study text only; the final quiz is taken online. Verify all references against the edition your agency has adopted.