

Nonredundant Steel Tension Members (NSTM) and Redundancy

The 2022 National Bridge Inspection Standards replaced the familiar term fracture critical member with nonredundant steel tension member (NSTM), and defined three kinds of redundancy that decide whether a steel tension member needs hands-on NSTM inspection. This course explains the definitions in 23 CFR 650.305, the NSTM inspection intervals and extended-interval criteria in 650.311(c), the procedures and FHWA approval path in 650.313(f) and (g), the qualification of NSTM team leaders in 650.309(c), and how NSTMs enter the critical findings rules of 650.313(q). It also covers FHWA's May 9, 2022 guidance memorandum on demonstrating system or internal redundancy, and the design-side fracture control concepts (Charpy toughness, the AASHTO/AWS D1.5 fracture control plan, and constraint-induced fracture) as summarized in the NSBA/AISC Steel Bridge Design Handbook and FHWA's fatigue repair manual. Regulatory text is quoted from the eCFR as published; confirm the current version and your agency's FHWA-approved procedures before applying it.

Learning objectives

- Define NSTM
- Explain redundancy types
- Describe NSTM inspection requirements
- Apply fracture control

From fracture critical to NSTM

In 1967, the Point Pleasant Bridge over the Ohio River in West Virginia, commonly called the Silver Bridge, collapsed. FHWA's Manual for Repair and Retrofit of Fatigue Cracks in Steel Bridges (FHWA-IF-13-020) describes the cause as brittle fracture of one of the nonredundant eyebars supporting the main span suspension system, and calls that eyebar truly fracture critical: the loss of a single steel tension element caused the collapse of the bridge. The manual notes that the eyebar was not typical bridge steel but heat-treated AISI 1060 steel, and that stress-corrosion cracking may have caused the initial flaw.

The response shaped U.S. bridge practice for half a century. The FHWA manual records that minimum Charpy impact requirements were first included in the ASTM A709 specification for bridge steels in 1974, and that a fracture control plan for bridges was implemented in 1975 to provide a higher level of safety for nonredundant structures. The national bridge inspection program, with periodic inspection and hands-on inspection of fracture critical members, grew from the same event.

For decades the key term was fracture critical member (FCM). The design handbook (NSBA/AISC Steel Bridge Design Handbook, Chapter 12, 2022) quotes the AASHTO LRFD definition: a steel primary member or portion thereof subject to tension whose failure would probably cause a portion of or the entire bridge to collapse. The FHWA repair manual uses essentially the same idea: a member in a system that cannot develop alternative load paths, whose fracture could lead to partial or total collapse.

The 2022 update to the National Bridge Inspection Standards (NBIS), 23 CFR 650 Subpart C, published May 6, 2022, introduced new terminology for inspection purposes. Section 650.305 defines a **Nonredundant Steel Tension Member (NSTM)** as "a primary steel member fully or partially in tension, and without load path redundancy, system redundancy or internal redundancy, whose failure may cause a portion of or the entire bridge to collapse." An **NSTM inspection** is "a hands-

on inspection of a nonredundant steel tension member," and **hands-on inspection** means "inspection within arm's length of the member," using visual techniques that may be supplemented by nondestructive evaluation.

The change is more than a rename. The NSTM definition names three distinct types of redundancy, and a member is an NSTM only if it has none of them. That framework makes explicit something the old FCM practice handled through a 2012 FHWA memorandum: some members without load path redundancy can still be shown, by approved analysis, not to cause collapse if they fracture. FHWA's May 9, 2022 memorandum replaced and rescinded the June 20, 2012 memorandum "Clarification of Requirements for Fracture Critical Members," and set out how agencies obtain approval of procedures to demonstrate system or internal redundancy.

Two vocabularies now coexist. Design specifications and fabrication documents, including AASHTO LRFD and the AASHTO/AWS D1.5 Bridge Welding Code as described in the 2022 handbook, still use fracture critical member for design and fabrication requirements. The NBIS uses NSTM for in-service inspection. Practitioners need to recognize both and understand that a member designed and fabricated as an FCM will normally be inspected as an NSTM unless an approved redundancy procedure says otherwise.

This course builds on BR-F01 (steel fatigue), which explains why tension members crack, and on BR-I01 (the 2022 NBIS) and BR-I02 (inspection intervals). It complements BR-I07 (steel inspection) and BR-I03 (critical findings).

Three kinds of redundancy

Section 650.305 defines three types of redundancy. Each has a precise meaning, and the differences decide whether a member requires NSTM inspection.

Load path redundancy is "a redundancy that exists based on the number of primary load-carrying members between points of support, such that fracture of the cross section at one location of a member will not cause a portion of or the entire bridge to collapse." It is the simplest and most common kind. A multi-girder bridge with many parallel stringers has load path redundancy: if one girder cracks through, the deck and cross-frames can shift load to adjacent girders.

FHWA's 2022 guidance gives a practical rule: for the purposes of NSTM identification, FHWA considers bridges with three or more primary load-carrying members to be load path redundant, and a determination of system or internal redundancy is not required for load path redundant members. The guidance adds that load path redundancy is typically determined from the number of primary members shown on the plans and verified by field inspection records. The classic nonredundant cases are therefore two-girder bridges, two-truss bridges, single and twin box (tub) girders where each box is a primary member, single-element tension ties, and many floor beam and cap configurations where a single member carries the load between supports.

System redundancy is "a redundancy that exists in a bridge system without load path redundancy, such that fracture of the cross section at one location of a primary member will not cause a portion of or the entire bridge to collapse." The member itself is unique in its load path, but the overall structure, through continuity, the deck, bracing and other components, can redistribute load after a fracture. FHWA's guidance says methods to establish system redundancy typically demonstrate, through refined structural analysis, that in the event of a fracture in a primary member the structural system redistributes load such that collapse is avoided. Key components of such analyses are the member failure scenarios, loading, linear and nonlinear material properties, boundary conditions, modeling requirements, and member and system performance criteria for each scenario.

The 2022 handbook describes the design counterpart, the System Redundant Member (SRM): a primary steel member in tension, or with a tension element, without load path redundancy but with redundancy in the bridge system, supported by

owner-approved calculation, analysis or other criteria supported by experimental verification. The handbook says SRMs are fabricated to D1.5 Clause 12, should satisfy the Charpy requirements for FCMs, and should have fatigue details designed for infinite life.

Internal redundancy is "a redundancy that exists within a primary member cross-section without load path redundancy, such that fracture of one component will not propagate through the entire member, is discoverable by the applicable inspection procedures, and will not cause a portion of or the entire bridge to collapse." Three conditions must all hold: the fracture must stay in one component; it must be discoverable by the inspection procedures; and the remaining section must prevent collapse. FHWA's guidance explains that methods typically demonstrate the remaining section will continue to safely carry dead and live load until the fracture is discovered, presumably at the next inspection, and that research has demonstrated the ability of sections built up from mechanically fastened components in certain structure types to prevent fracture of one element from propagating to connected elements. A riveted or bolted built-up girder, where a crack in one angle or plate is arrested at the fastener interface, is the classic candidate. A welded plate girder, where the web and flanges are continuous through welds, generally is not.

A useful way to remember the three: load path redundancy is about how many members there are; system redundancy is about whether the structure as a whole can carry load around a fractured member; internal redundancy is about whether the member itself can survive a fracture of one of its pieces until inspectors find it.

Identifying NSTMs and documenting them

The NBIS begins with documentation. Section 650.313(f)(1) requires the agency to "identify the locations of NSTMs in the bridge files." FHWA's 2022 guidance notes this necessitates identifying steel bridges without load path redundancy, system redundancy or internal redundancy.

Several elements of the NSTM definition need careful reading in practice.

Primary member. The definition applies to primary members. Secondary members such as lateral bracing that does not carry primary load are not NSTMs. The 2022 handbook, describing AASHTO LRFD Article 6.6.2.1 and Table 6.6.2.1-1, explains that designs designate members as primary or secondary and that designating secondary members as primary invokes more costly fabrication and testing without adding significant value. For design purposes the handbook also states that secondary members, and diaphragm or cross-frame members in horizontally curved bridges, should not be designated as FCMs.

Steel. The definition is limited to steel. Prestressed concrete, reinforced concrete and timber members are outside it, even if they are single load paths.

Fully or partially in tension. A member need not be entirely in tension. The tension flange of a two-girder bridge and the tension portion of its web are partially in tension and qualify. The handbook notes, for design classification, that primary steel members not subject to a net tensile stress under Strength I are not to be classified as FCMs. Agencies' identification procedures commonly delineate tension zones, for example the positive moment regions of continuous two-girder spans, so inspectors know where hands-on effort is required.

Whose failure may cause collapse. The NBIS uses "may cause," while the AASHTO FCM definition the handbook quotes uses "would probably cause." The inspection definition is therefore at least as inclusive as the design one.

Common NSTM configurations encountered in inventories include: two-girder systems (plate girders or rolled beams); two-truss systems, where tension chords, diagonals, verticals and eyebars are NSTMs unless shown otherwise; single or twin steel

box girders; steel pier caps and straddle bents carrying girders, where the cap's tension flange or tension zone is a single load path; pin-and-hanger assemblies in suspended spans; tied arch tie girders; floor beams in two-girder or two-truss systems where floor beam spacing means a single floor beam fracture could drop the deck; and suspension bridge eyebars chains. The specific classification of any member depends on the agency's procedures and the bridge's actual framing.

Bridge files should identify not just that a bridge has NSTMs but where they are. Good practice, consistent with 650.313(f)(1) and (g), includes framing plans or sketches that mark NSTMs and their tension zones, the specific details on each NSTM that are prone to fatigue or fracture, and the access method needed to reach them. FHWA's guidance on redundancy procedures lists details that might affect redundancy, including pin and hanger connections, nonredundant eyebars, plug welds or discontinuous backing bar splices, and constraint-induced fracture prone, other fracture prone, or stress concentrating details. The same list is a useful checklist for what the bridge file should flag on any NSTM.

Identification is also tied to the inspection condition rating. The NBIS references an NSTM Inspection Condition item in the National Bridge Inventory, used both to set intervals and to define critical findings. BR-S02 discusses SNBI condition data.

Inspection intervals for NSTMs

Section 650.311(c) states that "NSTMs must be inspected at regular intervals not to exceed the interval established using one of the risk-based methods" in paragraphs (c)(1) or (c)(2). The two methods mirror those used for routine and underwater intervals; BR-I02 covers the interval framework generally.

Method 1 is a simplified assessment of risk that classifies each bridge into one of three categories with an interval not to exceed 12, 24 or 48 months.

Regular intervals. Under 650.311(c)(1)(i), each NSTM must be inspected at intervals not to exceed 24 months, except as required by the reduced-interval rules or allowed by the extended-interval rules.

Reduced intervals. Under (c)(1)(ii)(A), agencies must develop and document criteria to determine when intervals must be reduced below 24 months. Factors to consider include structure type, design, materials, age, condition, environment, annual average daily traffic and truck traffic, history of vehicle impact damage, loads and safe load capacity, and other known deficiencies. Under (c)(1)(ii)(B), NSTMs rated in poor or worse condition, recorded by the NSTM Inspection Condition item coded 4 or less, must be inspected at intervals not to exceed 12 months.

Extended intervals. Under (c)(1)(iii)(A), NSTMs may be inspected at intervals not to exceed 48 months only if all of the following criteria are met:

1. The bridge was constructed after 1978, as recorded in the NBI Year Built item, and fabricated in accordance with a fracture control plan.
2. All NSTMs have no fatigue details with finite life.
3. All NSTMs have no history of fatigue cracks.
4. All NSTMs are rated satisfactory or better, NSTM Inspection Condition item coded 6 or greater.
5. The bridge's inventory rating is at least the standard AASHTO HS-20 or HL-93 loading and routine permit loads are not restricted or not carried/issued, recorded by an Inventory Load Rating Factor of 1.0 or greater and the Routine Permit Loads item coded A or N.
6. All NSTMs do not include pin and hanger assemblies.

Agencies that use extended intervals must develop and document an extended interval policy and notify FHWA in writing before implementation, under (c)(1)(iii)(B).

Method 2 uses a more rigorous risk assessment. The policy and criteria must be submitted for FHWA approval, and each bridge must be classified into one of three risk categories with an NSTM interval not to exceed 12, 24 or 48 months.

The extended-interval criteria are a compact summary of what makes an NSTM higher or lower risk. Post-1978 construction with a fracture control plan addresses material toughness and fabrication quality. Infinite-life fatigue details and no crack history address the likelihood that cracks will start, connecting directly to BR-F01: a detail whose stress range is below its constant-amplitude threshold should not crack. Good condition and full inventory rating address deterioration and loading. And pin-and-hanger assemblies, which have a history of corrosion-induced freezing and nonredundant failure, are excluded outright.

First inspections. Section 650.313(f)(3) requires the first NSTM inspection for each bridge, and for each bridge with rehabilitated NSTMs, "as soon as practical, but within 12 months of the bridge opening to traffic." This captures fabrication and erection defects early, the period when the FHWA repair manual notes that susceptible details or materials usually fracture as loads are first applied, citing the 1970 Bryte Bend Bridge fracture during construction.

Illustrative example (not a real bridge): a 1992 two-girder bridge fabricated under a fracture control plan, with all Category C or better details on infinite life, no crack history, NSTM rating 7, inventory rating factor 1.15 for HL-93 and unrestricted permits, and no pins or hangers, could qualify for a 48-month interval under an agency's documented extended interval policy. The same bridge with a history of one repaired web gap crack would not, because criterion 3 fails.

Procedures, access and the hands-on standard

Section 650.313(f)(2) requires agencies to "perform hands-on inspections of NSTMs in accordance with the procedures developed in paragraph (g)." Paragraph (g) requires agencies to "develop and document inspection procedures for bridges which require NSTM, underwater, in-depth, and complex feature inspections in accordance with Section 4.2, AASHTO Manual," incorporated by reference. General procedures applicable to many bridges can be in the agency procedures manual, but "specific procedures for unique and complex structural features must be developed for each bridge and contained in the bridge file."

The hands-on standard is defined: inspection within arm's length of the member, using visual techniques that may be supplemented by nondestructive evaluation. The FHWA repair manual explains why: hands-on inspection places inspectors in close proximity to effectively identify problems. FHWA's 2022 guidance puts the rationale in terms of crack tolerance. Bridges with NSTMs are at elevated risk of sudden collapse because the system or member cannot redistribute load after full or partial fracture, which leads to a lower tolerance for fatigue cracking. Hands-on inspection mitigates that risk by identifying cracks at early stages of growth, before they propagate through or fracture the section.

In practice, a bridge-specific NSTM procedure typically addresses the following (a teaching summary, not a quotation of the AASHTO Manual):

- **Member and detail identification.** A framing sketch marking each NSTM, its tension zones, and the specific fatigue- and fracture-prone details: cover plate ends, web gaps at connection plates, lateral gusset terminations, intermittent welds, plug welds, backing bars, copes, pin and hanger assemblies, floor beam connections, and any previous repairs.
- **Access.** The equipment needed to bring the inspector within arm's length of every NSTM surface: snooper or under-bridge inspection vehicle, bucket truck, lift, rigging, rope access, interior access for box girders with confined space

precautions, and traffic control.

- **Cleaning and NDE.** Where paint, debris or corrosion obscures details, the procedure may call for cleaning and for dye penetrant, magnetic particle, ultrasonic or other testing at specified details. BR-F01 summarizes the field methods described in the FHWA manual.
- **Known defects.** A list of previously documented cracks, drilled holes, retrofits and corrosion, with instructions to measure and compare against prior records.
- **Reporting.** Documentation of each detail, photographs, sketches and measurements, plus escalation steps for findings.

Box girders deserve particular mention. Their NSTM surfaces are often inside the box, requiring confined space entry, lighting and ventilation. FHWA's redundancy guidance lists, among special inspection requirements, visual inspection of interior members and connections of box girders at a prescribed interval. Interior inspection is also where the FHWA repair manual notes birds can enter through unplugged drilled holes, one reason it recommends plugging holes in box girders.

Team leaders matter as much as access. Section 650.309(c) requires team leaders on NSTM inspections to meet the general team leader requirements, complete an FHWA-approved training course on the inspection of NSTMs and score 70 percent or greater on an end-of-course assessment, with prior FHWA-approved NSTM training before June 6, 2022 satisfying the intent, and to satisfy these requirements within 24 months from June 6, 2022. General team leaders must also complete 18 hours of FHWA-approved refresher training over each 60-month period under 650.309(b)(3). This LoadPath PDH course is supplemental PDH and is not FHWA-approved NSTM training or NBIS refresher training.

Demonstrating system or internal redundancy

Agencies are not required to accept every member without load path redundancy as an NSTM. Section 650.313(f)(1)(i) says an agency "may choose to demonstrate a member has system or internal redundancy such that it is not considered an NSTM," by developing and submitting a formal request for FHWA approval of procedures using a nationally recognized method. FHWA reviews the procedures for conformance with that method. The request must include:

- A. Written policy and procedures for determining system or internal redundancy.
- B. Identification of the nationally recognized method used.
- C. Baseline condition of the bridges to which the policy is applied.
- D. Description of design and construction details on the members that may affect system or internal redundancy.
- E. Routine inspection requirements for bridges with system or internally redundant members.
- F. Special inspection requirements for those members.
- G. Evaluation criteria for when members should be reviewed to ensure they still have system and internal redundancy.

The regulation defines nationally recognized: "developed, endorsed and disseminated by a national organization with affiliates based in two or more States; or currently adopted for use by one or more State governments or by the Federal Government; and is the most current version." Under 650.313(f)(1)(ii), the bridge is then inspected using the approved routine and special inspection methods.

FHWA's May 9, 2022 guidance names two methods it considers nationally recognized: the AASHTO Guide Specifications for Analysis and Identification of Fracture Critical Members and System Redundant Members, and the AASHTO Guide Specification for Internal Redundancy of Mechanically-Fastened Built-Up Steel Members. Other methods can qualify by meeting either regulatory criterion; the guidance notes AASHTO would be one such national organization, and that methods recognized by FHWA and adopted by state DOTs between 2012 and 2022 would satisfy the adoption criterion. The memo also

required agencies with previously approved system redundant member procedures to update them to meet 650.313(f)(1) and submit them for approval by June 6, 2024.

The guidance cites the research foundation for these methods, including NCHRP Report 319 on two-girder redundancy (1989), NCHRP Report 883 on fracture critical system analysis (2018), an FHWA study of member and load path redundancy on the US-421 bridge over the Ohio River (FHWA-HRT-13-105, 2013), a Texas study of fracture critical steel box-girder response, and Purdue research on member-level redundancy of built-up steel girders and axially loaded members.

FHWA uses a review table (Table 1 of the guidance) listing indicators for each required component. Under baseline condition, it lists conditions that might affect applicability of the method: presence of fatigue cracks, fatigue life considerations, severity and extent of corrosion, and impact damage. Under design and construction details, system redundancy relies on absence of pin and hanger connections, nonredundant eyebars, plug welds or discontinuous backing bar splices, and constraint-induced fracture prone, other fracture prone, or stress concentrating details. Internal redundancy relies on section proportions and connections, the ability to identify a faulted member during routine inspection, sufficient capacity in the faulted state, and the ability of the faulted member to function in service until the next inspection without further damage to intact components. Under routine inspection, it lists interval, access methods, and focus areas. Under special inspection, it lists visual inspection of box girder interiors at a prescribed interval and inspection intervals for internally redundant members. Under evaluation criteria, it lists defects that reduce capacity or stability such as corrosion section loss, impact or fire damage, and repairs or retrofits.

The final element is essential. FHWA's guidance emphasizes that redundancy established through analysis relies on the continued ability of the members in the alternate load path to carry the loads identified in the faulted-state analysis. Procedures must identify those members for routine inspection, and must establish when damage or deterioration to them requires reevaluation. A two-girder bridge shown to be system redundant because of its deck and cross-frames is only redundant as long as the deck and cross-frames remain sound.

Fracture control in design and fabrication

Inspection is the last line of defense. The first lines are material toughness, detailing and fabrication, which together form fracture control. The 2022 handbook explains that fracture of steel bridge members is typically precluded through material selection, specifying minimum fracture toughness for each grade based on minimum expected temperature and thickness, and that a Fracture Control Plan per AASHTO/AWS D1.5 Clause 12 provides a higher level of safety for fracture critical members. It describes a fracture control plan as a holistic approach that includes everything affecting the potential for fracture: design, detailing, materials, fabrication and inspection.

Toughness and Charpy testing. The handbook describes the Charpy V-notch (CVN) test: a small notched bar is broken by a swinging pendulum, and the absorbed energy is measured from the difference in swing height. Repeating tests at different temperatures shows how steel becomes brittle, absorbing less energy, as temperature drops. Bridge steel specifications require an energy level in the transition region at a temperature tied to the lowest service temperature. AASHTO LRFD Table 6.6.2.1-2 defines three temperature zones based on minimum service temperature; higher CVN requirements apply to higher grades, thicker material and lower service temperatures, and requirements for fracture critical members are more severe than for non-fracture-critical members. The values are specified in ASTM A709 and tabulated in AASHTO LRFD Table C6.6.2.1-1.

The handbook states that unless otherwise indicated on the plans, CVN testing is required for primary members or components subject to net tensile stress under Strength I, or portions in designated tension zones, with exceptions for

diaphragm and cross-frame members and their gusset plates in horizontally curved bridges. Contract plans must designate primary members subject to net tension.

Two aspects of the fracture control plan. The FHWA repair manual describes the two main aspects of the AASHTO/AWS fracture control plan: control of cracks, through detailing and enhanced fabrication inspection protocols; and specification of minimum material properties for steel and weld metal measured by CVN testing. Both are integral to an acceptably low probability of brittle fracture. The Bridge Welding Code provisions should keep discontinuities small enough to prevent sudden fracture and ensure the fatigue crack growth threshold is not exceeded under service loads, with a higher standard for fracture critical members.

Design responsibilities. The handbook says the designer is responsible for determining which members lack load path redundancy and should be classified as FCMs, and that FCM locations must be clearly indicated on the contract plans. FCMs are fabricated to D1.5 Clause 12 and receive routine inspections plus hands-on in-service inspections per 23 CFR 650. The handbook also describes the fatigue requirement covered in BR-F01: for details on fracture critical tension members, the Fatigue I check with infinite-life resistance must be used regardless of traffic volume.

Why the date matters to inspectors. The FHWA manual notes that for bridges designed after 1974, CVN properties may be assumed at least equal to the A709 minimums if records are unavailable, but cautions against treating 1974 as firm because design and construction dates can straddle it; older steel may need cores tested, at least three Charpy specimens per plate or shape. The NBIS extended-interval criterion of construction after 1978 with a fracture control plan reflects the same history. Pre-1975 NSTMs may have unknown toughness, details designed under older fatigue rules, and welds not made to modern standards, which is why they generally receive more attention.

Constraint-induced fracture and other fracture-prone details

Not all fractures begin with a fatigue crack. The FHWA repair manual notes that fracture can occur directly without previous fatigue crack growth after years of service, citing the Hoan Bridge. Brittle fracture can occur at high constraint details with little or no warning. Constraint develops when vertical and horizontal attachments are welded to girder webs, even thin ones: intersecting welds create a triaxial stress state in which the material cannot yield through its thickness, generating localized stresses much higher than yield.

The 2022 handbook lists three conditions that together elevate the risk of constraint-induced fracture: a high level of net tensile stress including residual stress; a high degree of constraint producing a three-dimensional stress state that prevents local yielding; and a crack-like or notch-like plane of discontinuity roughly perpendicular to the primary tensile stress. It notes that intersecting welds do not necessarily create susceptibility, particularly with fewer than three intersecting welded elements, such as flange-to-web welds crossing shop splices. The handbook cites the Hoan Bridge and SR 422 over the Schuylkill River as documented cases.

The handbook describes how current details avoid the problem. Where a longitudinal stiffener parallel to the primary stress meets a transverse stiffener or connection plate in a net tension region, the longitudinal element should be continuous and the transverse element discontinuous, attached with fillet welds; groove welds are not necessary and should not be used. A gap of about 3/4 inch between weld toes is recommended where a gap is specified, but not less than 1/2 inch. AASHTO LRFD Tables 6.6.1.2.4-1 and 6.6.1.2.4-2 provide recommended details for these intersections and for lateral connection plates.

For NSTM inspection, these details are high-priority targets. A web where a horizontal lateral gusset plate meets a vertical connection plate with intersecting welds, on a two-girder bridge, is exactly the condition the handbook describes. Inspectors

cannot see triaxial constraint, but they can recognize the geometry and confirm that the bridge file flags it. FHWA's redundancy guidance lists constraint-induced fracture prone details among those whose absence a system redundancy procedure may depend on.

Other fracture-prone conditions from the sources:

- **Low-toughness steel at reentrant corners.** The 1970 Bryte Bend Bridge fracture during construction was attributed to low-toughness A514 steel (minimum yield 100 ksi) at a reentrant corner between a transverse bracing member and a tub girder tension flange, combined with a preexisting weld toe crack from fabrication and shipping.
- **Eyebars and hangers.** The FHWA manual says eyebars usually come with low redundancy, so most can be classified as FCMs; fabrication flaws can initiate fatigue cracks. It states there are no repair methods that can be recommended for cracked eyebars and hangers; the options are new members with improved fabrication and toughness, or added redundancy, with parallel post-tensioning tendons or bars as a temporary secondary load path.
- **Plug welds and discontinuous backing bars.** Named in FHWA's redundancy guidance as details whose presence affects system redundancy.
- **Stress-corrosion cracking.** The FHWA manual notes it is primarily a concern for very high-strength steels and has occurred in prestressing cables, A490 bolts and out-of-specification A514 plate.
- **Gusset plates.** Truss gusset plates connecting NSTM members may themselves be critical; BR-L05 covers gusset plate evaluation.

Responding to cracks and damage on NSTMs

A crack in an NSTM is a different event from a crack in a redundant member. The FHWA repair manual says the development of a fatigue crack in a fracture critical member should warrant immediate action, such as closure of one or more lanes, posting the bridge for cars only, or complete closure until repairs can be made. For redundant members, keeping the bridge open may be justified, but a fracture assessment must still show the probability of fracture at service loads is acceptably small.

The NBIS formalizes escalation through critical findings. Section 650.313(q) requires agencies to document procedures to address critical findings in a timely manner, defining them "considering the location and the redundancy of the member affected and the extent and consequence of a deficiency." Deficiencies include, but are not limited to, scour, damage, corrosion, section loss, settlement, cracking, deflection, distortion, delamination, loss of bearing, and any condition posing an imminent threat to public safety. At a minimum, procedures must include findings that warrant full or partial closure of any bridge, and findings that warrant "an NSTM to be rated in serious or worse condition," defined by the NSTM Inspection item coded 3 or less. Redundancy is thus written directly into how critical findings are defined. BR-I03 covers the full critical findings process, including notification timelines.

The response sequence for a crack on an NSTM, drawn from the FHWA manual and summarized here as a teaching aid:

1. **Secure safety.** Follow the agency's critical finding procedure. The engineer of record or bridge owner decides on lane closure, load restriction or full closure.
2. **Characterize the crack.** Locate tips with dye penetrant or magnetic particle testing, measure, photograph and determine orientation relative to the primary stress.
3. **Inspect similar details.** The manual calls a special in-depth inspection for other cracks the first and most urgent step, prioritizing details on fracture critical members and those with high live-load stress ranges.
4. **Assess fracture potential.** Fracture mechanics assessment requires material toughness, from mill reports, assumed A709 minimums for post-1974 design with caution, or tested cores.

5. **Arrest and repair.** Drill the crack tip (minimum 1 inch diameter per the manual) and add bolted splice or doubler plates sized like a bolted field splice. For eyebars and hangers, provide a temporary secondary load path and plan replacement.
6. **Retrofit similar details and reevaluate.** If an agency relies on approved system or internal redundancy, FHWA's guidance requires criteria for when damage or repairs trigger reevaluation of that redundancy.

Damage other than fatigue counts too. Vehicle impact, fire, and corrosion section loss on NSTMs reduce capacity directly and, for system redundant members, may compromise the alternate load path. FHWA's Table 1 lists impact or fire damage, corrosion section loss, and repairs or retrofits as evaluation triggers. A damage inspection after an over-height truck strike on a two-girder bridge or a through-truss portal should be planned with NSTMs in mind.

Load rating ties in as well. A significant NSTM defect usually triggers a load rating review, covered in BR-L04, and the extended interval criteria require an inventory rating factor of at least 1.0. A crack repair that changes the section should be reflected in the rating model.

Where cracks start on NSTMs: details to target

Hands-on inspection is only as good as the inspector's knowledge of where to look. The FHWA repair manual and the 2022 handbook identify the details that most often crack in steel bridges, and on an NSTM each is a priority. This section connects the fatigue concepts of BR-F01 to NSTM field work.

Low-category welded attachments in tension zones. The handbook explains that attachments such as cover plates, gussets and stiffeners welded to a web or flange introduce a transverse weld toe, a line of elevated tension where fatigue cracks start from small, sharp discontinuities. Cover plate ends on rolled beams are the classic case; the FHWA manual describes the cover plate termination on the I-95 Yellow Mill Pond bridge as a Category E' detail. On an NSTM tension flange, any such detail deserves close examination at the weld toe, where a crack grows first as a semicircle into the flange before breaking through.

Lateral gusset plates welded to webs. The handbook classifies the base metal at the termination of a horizontal lateral connection plate weld to a web as Category E, and the FHWA manual identifies two potential crack sites at web gusset plates, including the gusset weld termination. Where a gusset also meets a transverse connection plate, constraint-induced fracture becomes a concern.

Web gaps. Distortion-induced cracking at connection plates not attached to the flange is, per the FHWA manual's cited estimate, the source of over 90% of fatigue cracking. On two-girder bridges, floor beam connection plates are a frequent site, because floor beam end rotation is restrained at the top by the deck. The handbook notes most distortion cracks start parallel to the primary stress, but after long growth they can turn perpendicular to it, which on an NSTM web is a serious condition.

Floor beam and stringer connections. The FHWA manual explains that connection angles assumed simple resist end rotation and crack because they are too thick, and that copes, often flame cut with poor radii, crack at nominally zero-stress locations. In two-girder and truss systems these connections carry the deck to the NSTMs.

Tack welds and intermittent welds. The manual notes temporary tack welds on older structures often crack; usually they are benign, but tack welds parallel to the primary stress are Category E, and the concern is a crack that propagates into the base metal of the tension element.

Pins, hangers and eyebars. These are excluded from extended NSTM intervals by the NBIS, and the FHWA manual says no repairs can be recommended for cracked eyebars and hangers.

Previous repairs. Drilled holes, bolted splices, and weld repairs need re-examination for crack reinitiation. The FHWA manual describes "swiss-cheese" reinitiation at web gaps where small holes were drilled repeatedly without removing the cause, and notes weld repairs of base metal often re-crack.

Corrosion and section loss. Although not fatigue, corrosion at joints, bearings and drainage outlets reduces NSTM capacity and can create notches. FHWA's redundancy guidance lists corrosion section loss among triggers for reevaluating system or internal redundancy.

Signs of cracking. The FHWA manual notes that working cracks bleed rust staining as crack faces rub, a useful pointer but not a complete inspection, and that dye penetrant and magnetic particle testing confirm and locate tips. The handbook adds that in laboratory tests up to 80% of fatigue life was consumed before a crack from an internal flaw reached the surface, so any visible crack on an NSTM should be treated as advanced.

Putting NSTM practice together

The NSTM framework links design, fabrication, inspection and evaluation. The following summary organizes the obligations and good practices from the sources by role. It is a teaching aid; the controlling documents are the NBIS, the AASHTO Manual for Bridge Inspection as incorporated by reference, and the agency's FHWA-approved procedures.

Program managers. Ensure NSTM locations are identified in bridge files (650.313(f)(1)). Maintain documented NSTM inspection procedures, with bridge-specific procedures for unique features (650.313(g)). Set NSTM intervals under Method 1 or Method 2, with documented reduced-interval criteria, the mandatory 12-month interval for NSTMs coded 4 or less, and, if used, a documented extended-interval policy with prior written notice to FHWA (650.311(c)). Schedule first NSTM inspections within 12 months of opening or rehabilitation (650.313(f)(3)). Verify NSTM team leader qualifications (650.309(c)). Include NSTM conditions in critical finding procedures (650.313(q)). If pursuing system or internal redundancy, submit procedures with all seven required elements for FHWA approval.

Team leaders and inspectors. Know which members are NSTMs and where their tension zones and fracture-prone details are. Get within arm's length of every NSTM surface. Use NDE where called for. Compare against prior records of cracks and repairs. Rate the NSTM Inspection Condition item consistently with SNBI guidance and escalate critical findings immediately.

Designers. Avoid nonredundant tension members where practical. Where they are unavoidable, mark FCMs and tension zones on the plans, specify fracture critical toughness and D1.5 Clause 12 fabrication, design fatigue details on FCMs for infinite life, and avoid constraint-induced fracture prone details by following AASHTO's recommended intersections. Remember the inspection consequences: every NSTM will need hands-on access for the life of the bridge, so provide access features such as interior access for boxes.

Load raters and evaluators. Account for NSTM condition in ratings. Where an agency has approved system redundancy, understand which members form the alternate load path and what deterioration would trigger reevaluation.

Owners making investment decisions. NSTM inspection is expensive because of access and specialized staff. Retrofit options include adding load paths, replacing pin-and-hanger assemblies, or pursuing approved redundancy analysis.

Key numbers to remember. NSTM interval: not to exceed 24 months regular; 12 months if coded 4 or less; up to 48 months only if all six extended criteria are met and a documented policy is in place. First NSTM inspection: within 12 months of opening or rehabilitation. Load path redundancy for NSTM identification: three or more primary load-carrying members, per FHWA's 2022 guidance. NSTM training assessment: 70 percent or greater. Critical finding minimum: NSTM coded 3 or less.

Finally, remember the lesson of 1967 that started it all: a single small flaw in a single tension member can bring down a bridge. The NSTM rules exist to find that flaw first.

Key takeaways

- An NSTM is a primary steel member fully or partially in tension, without load path, system or internal redundancy, whose failure may cause a portion of or the entire bridge to collapse (23 CFR 650.305).
- Load path redundancy depends on the number of primary members; FHWA's 2022 guidance treats three or more as load path redundant.
- System redundancy means the bridge system can survive fracture of a primary member; internal redundancy means a fracture of one component will not propagate, is discoverable, and will not cause collapse.
- NSTM inspection means hands-on, within arm's length, per documented procedures (650.313(f)(2), (g)).
- NSTM intervals: not to exceed 24 months; 12 months if the NSTM Inspection Condition is coded 4 or less; up to 48 months only if all six criteria in 650.311(c)(1)(iii) are met and a policy is documented.
- The first NSTM inspection is required within 12 months of opening to traffic or after NSTM rehabilitation (650.313(f)(3)).
- Agencies may obtain FHWA approval of procedures using nationally recognized methods to show system or internal redundancy; the procedure must include seven elements including reevaluation criteria.
- NSTM team leaders need FHWA-approved NSTM training with a 70% or better end-of-course assessment (650.309(c)).
- Critical finding procedures must include findings that warrant an NSTM rated 3 or less (650.313(q)).
- Fracture control relies on Charpy toughness, D1.5 Clause 12 fabrication, infinite-life fatigue details and avoiding constraint-induced fracture prone details.

References

1. 23 CFR Part 650, Subpart C — National Bridge Inspection Standards (final rule published May 6, 2022)
2. FHWA, Manual for Repair and Retrofit of Fatigue Cracks in Steel Bridges, FHWA-IF-13-020, 2013
3. FHWA, Memorandum: ACTION: Inspection of Nonredundant Steel Tension Members, with attachment Guidance for the Approval of Procedures for Determining System or Internal Redundancy for Steel Tension Members without Load Path Redundancy, J. L. Hartmann, HIBS-40, May 9, 2022
4. NSBA/AISC, Steel Bridge Design Handbook, Chapter 12: Design for Fatigue, February 2022 (Section 3.3, Fracture Control)

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