# Inspection of Fracture Critical Bridge Members

Ron L. Purvis

**Beginning in 1987, the Federal Highway Administration sponsored a 2-day training course entitled "Inspection of Fracture Critical Bridge Members." The course was developed and taught by Byrd, Tallamy, MacDonald and Lewis Consulting Engineers. It was attended by Federal Highway Administration state and local bridge inspectors who have responsibility for on-site inspection of highway bridges. All state and most local agencies responsible for existing bridges have inspection programs in place. Certain modifications may be necessary, in addition to inspector training, if fracture critical members are to be inspected in accordance with the guidelines provided in the course. The guidelines require that each fracture critical member receives a hands-on, close-up 360° inspection. Additional nondestructive testing may be appropriate if a potential fracture is identified. Additional resources may be required to provide this level of inspection. The inspector is often not in a position to budget and schedule these resources. Fracture critical members should be first identified by a qualified bridge engineer. It is recommended that each agency include in its program a procedure for documenting and flagging each fracture critical member to ensure that it receives appropriate priority when the bridge is inspected. An inspection plan is formulated for each bridge with fracture critical members that include equipment, inspection technique, and staffing. The potential for fatigue cracks is evaluated and locations identified. The plan is then discussed with the inspector to ensure that the priorities are understood.**

The following provides an overview of the implementation of an inspection program for fracture critical bridge members.

## BACKGROUND

### National Bridge Inspection Program

The National Bridge Inspection Standards (NBIS) administered by the U.S. Department of Transportation, Federal Highway Administration (FHWA) are almost 20 yr old. It is the law that all highway bridges open to the public must be inspected at 2-yr intervals for safety. Bridges with restricted capacity or certain structural problems are normally inspected more frequently. Some agencies require that the inspector be a registered professional engineer. Minimum requirements are that the team leader have 5 yr of related experience and successfully complete a training course.

R. L. Purvis, Byrd, Tallamy, MacDonald and Lewis Division, Wilbur Smith Associates, 2921 Telestar Court, Falls Church, Va. 22042.

### Quality of Inspection

In most situations the only method available to detect flaws in a bridge member is visual inspection. It is important to identify the flaws early in the typical crack-development scenario. If the defect is identified as soon as it can be seen by the inspector, the service life of the member often has been reduced by more than 80 percent. Fractures have occurred on bridges that have been open to traffic for relatively short periods of time. On such a structure, there may be only one opportunity for the inspector to identify the flaw and prevent the fracture. If the fracture is likely to cause a sudden failure of all or part of the bridge, it is extremely important that the defect be identified in time to prevent a possible catastrophe.

The flaw is often very small. The inspector has to be close, to know where to look, and to recognize the crack when it first becomes visible. A supplement to the FHWA Bridge Inspector's Training Manual has been developed along with a 2-day advance training course to provide instructions in this area. The manual and course were developed by the Byrd, Tallamy, MacDonald and Lewis Division of Wilbur Smith Associates, consulting engineers, under the sponsorship of the FHWA.

## IDENTIFYING FRACTURE CRITICAL BRIDGES

### Definition of a Fracture Critical Member

A fracture critical bridge must have one or more fracture critical members (FCMs). An FCM is a tension member or component whose failure will produce a sudden collapse of the structure. The training course is developed on a level to include the non-engineer inspector and the theory is presented accordingly. The participant is taught how to identify a tension member and to determine whether its failure will result in an immediate bridge collapse. The portion of a member in tension is being pulled apart. This causes cracks to grow and leads to fracture. A member in axial tension is stressed uniformly throughout the cross section for the total length between connections.

Hangers, suspension cables, and some truss members normally are stressed in axial tension. The stress varies throughout members that are in bending. The inspector must be aware of tension zones in such members. For example, on a simple beam, maximum tension is in the bottom flange at midspan. An equally important location on a continuous span is the top flange over the support. High stress may also be concentrated at locations along a member where the cross section changes or where there is a discontinuity.

### Redundancy

For the inspector to determine whether a sudden collapse will occur when a member fractures, it is necessary to understand the term redundancy as it applies to primary bridge members or connections. Redundancy is the ability of other members to help carry the load when a member becomes weak or fails. Three different types of redundancy are possible depending on the design. These are load path, structural, and internal.

Load path redundancy relates to the minimum number of members required to support the deck under traffic. A bridge with fewer than three girders or trusses is considered nonredundant and therefore fracture critical. Bridges with three or more girders are considered redundant, because if one girder becomes weak the others will help carry the load. There are degrees of redundancy that should be considered depending on the girder spacing, stiffness of the deck, and framing system. A capacity analysis by a structural engineer may be necessary to predict the failure scenario on some bridges.

Structural redundancy relates to the support provided by the cantilever created after a continuous member is weakened. This occurs only on interior spans with members continuous across supports on both ends. There must be a minimum of three continuous spans to have a structurally redundant span that is located in the center.

Internal redundancy relates to crack propagation through the cross section of a member. Many members are composed of several parts. A crack must reinitiate in each part on internally redundant members. Built-up members with plates attached by rivets or bolts have internal redundancy. Others are reinforced concrete, cables, and members composed of several separate sections. Rolled steel members have no internal redundancy, nor do built-up welded members. As fatigue and fracture of steel members are studied, it is found that cracks not only propagate freely through welds, they often start because of the weld.

Many agencies define FCMs in terms of load path redundancy. Structural and internal redundancy, however, are also considered in evaluating problems. Examples of fracture critical spans are spans supported by two or fewer single web girders, box girders, trusses, suspension cables, cross girders, caps, and tie members on tied arch spans. Spans supported by four or fewer pin-and-hanger assemblies also qualify.

## FATIGUE AND FRACTURE

### Predicting Fracture

It is important that the inspector identify a crack or flaw before the member fractures. Physical characteristics make certain members more susceptible to fracture. The magnitude of the total stress or the number of times a member is stressed, or both, contribute to the fracture. Also, design details have an important influence on crack initiation. The remaining factor is flaws in the member. The inspector's efficiency at identifying FCM problems is significantly enhanced by an understanding of fatigue and fracture.

Fractures require a driving force. Normally this force is produced by the load on the structure. The force on a particular cross section of the member is called stress. The stress may take the form of compression, tension, or shear. Compression squeezes or pushes down on a member. Cracks normally do not cause problems in compression members because the material is not being pulled apart. If a crack exists in a compression member (which is rare), there is no force to make it grow. Tension stretches or pulls a member apart. Cracks are of concern in tension members because the stress causes the member to fracture. The cracks grow perpendicular to the direction of the tension stress. Shear is similar to tension, but rather than pulling the member apart it tends to tear or slice the material. Some cracks grow as a result of shear. The direction of a shear crack is at a 45 degree angle to the force. Bridge members may be subjected to only one or a combination of these stresses.

The fracture may be the result of an overload in which the member is stressed beyond its capacity or yield point. This rarely occurs on bridges designed to carry standard legal loads. More often cracks are caused by repeated loads that do not exceed the legal limit. Fatigue is the term used to describe the process of material damage caused by repeated loads. One load is a cycle. A cycle must subject the member to a certain magnitude of change in stress or stress range before it is significant in causing fatigue cracks. Bridges that carry a large volume of heavy loads are more likely to experience fatigue problems.

Fatigue crack initiation is not only related to the number and size of the stress cycle, it is also related to design details. Stress concentrates at locations where the rigidity of the member changes. Fatigue occurs at points of stress concentration. Details that cause changes in the rigidity of the member have been categorized to help the designer avoid cracking problems. These categories are used by the inspector to predict crack initiation in existing bridges.

All bridge members have flaws. Their size and location influence crack initiation and propagation. Flaws provide a focus of crack initiation. It may be in the base metal of the member or in the weld metal. Many flaws are not visible. Nondestructive testing (NDT) is used to identify these flaws during the shop inspection. On older bridges NDT was not always required. Field welds and repair welds often do not receive NDT. Flaws in the base metal may be caused by fabrication, transportation, erection, or in-service damage. Such flaws include bolt and rivet holes, notches, grinding marks, copes, and flame cuts. Service flaws include collision damage, damage from improper straightening, or section loss caused by corrosion.

### Material Consideration

There are two types of fracture: ductile and brittle. When ductile fracture occurs, the material stretches before it separates into two parts. The fracture is slow and there is often time to prevent a disaster. A brittle fracture occurs very rapidly. The brittle fracture is of particular concern to the bridge inspector. Certain members are more likely to fail by brittle fracture. Members composed of thick plates are more likely to have a brittle fracture than members made of thinner plates. They tend to break rather than bend. Also, the colder the temperature, the more likely the occurrence of a brittle fracture. The tougher the steel, the less likely it is to fracture. Bridges designed today contain steel meeting these specifications, but they can be tested to determine the steel toughness. Information on the steel toughness is of benefit to the inspector in predicting potential problems.

### Design Consideration

Fatigue cracks start at locations in steel members where the rigidity of the member changes. These locations are created by designers attempting to save material. Cover plates are added to beams to avoid using a larger size. Stiffeners permit the use of very thin webs on members. As the member bends under a load, stress is concentrated at areas where the rigidity in the member changes. Cracks begin at these locations.

Fatigue cracks may be a result of either in-plane or out-of-plane bending. In-plane bending is a result of load distributed from the floor directly to the member. Out-of-plane bending is usually the result of the load's being transferred to the member through secondary members. This force tends to twist the member, and may be transmitted into thin parts of the members, such as the web, that were not designed to resist the stress. A crack may begin in the web in the space between the connection plate or stiffener and the flange. Often the crack is not perpendicular to the primary stress, therefore it does not represent as immediate a problem as the crack caused by in-plane bending. Inspectors, however, are cautioned to bring any cracks to the attention of a qualified structural engineer for evaluation.

### Loads on the Structure

Another factor that influences whether the fracture is brittle or ductile is the loading rate. Static loading is least likely to produce brittle fracture, whereas dynamic loading often results in a brittle or sudden fracture. Bridges experience a combination of static and dynamic loading. Inspectors should be aware of situations in which the dynamic loading is exceptionally high. Examples are bridges that receive heavy pounding loads, which might be caused by low approaches or poor vertical alignment.

Fatigue cracking is caused by repeated loads that produce stress cycles. Larger loads create stress cycles that cause fatigue damage. A certain design detail may be capable of carrying a limited number of stress cycles that are created by the larger loads using the structure. When the number of cycles exceeds the limit, cracking occurs at predictable locations. The inspector should know about the loading history of a bridge before conducting an evaluation.

### Crack Initiation and Propagation

Most cracks in steel bridges occur at predictable locations. Cracks occur at areas of stress concentration. They normally originate at a flaw. The flaw is often associated with a weld. When a fatigue crack caused by in-plane bending grows to a size visible to the inspector, at least 80 percent of the service life of the member has already expired. The small crack has been growing beneath the surface in a semi-elliptical pattern. After the crack reaches the surface it must penetrate through the paint before it is visible to the inspector. Occasionally the visibility is accentuated by rust stains that are associated with the crack.

NDT is available to help verify the existence of a crack. After the crack has been found, these tests will locate its boundaries and measure the size. In general inspection, however, NDT is not very effective in helping to find cracks that have not been identified.

## IMPLEMENTING A FRACTURE CRITICAL BRIDGE INSPECTION PROGRAM

### Modifying Existing Program

The purpose of fracture critical inspection training is to help prevent sudden bridge collapse. For the most effective use of resources, the level of inspection should be appropriate to the criticality of the member. Agencies normally do not have the resources to enable inspectors to perform hands-on, close-up, 360° inspections of all the components of all their bridges once every 2 yr. FCMs, however, should receive this level of inspection. To implement necessary fracture critical inspection procedures into an existing program, the following are needed:

1. Inspectors trained for required level of inspection,
2. Identification of fracture critical members,
3. Budgeting of adequate resources and planning for implementation of activities,
4. Inclusion of quality control procedures to monitor the program.

### FCM Inspection Training

Many bridge inspectors are not graduate engineers. For them to be effective, it is important that they understand where to look for problems. They should also know how to look, what to look for, and what to do if they find a potential problem. An ongoing FCM inspection training program is necessary for the required results to be achieved. Bridge inspection training must also extend beyond the classroom. Bridge inspectors normally work independently. A new inspector should demonstrate an understanding of the job before working alone. Certain personal traits should also be demonstrated. The job requires an attitude of perseverance and diligence. An inspector may often look at several hundred details having no problem before a flaw is found. The temptation to take short cuts is great. Inspectors should be continually monitored to ensure that a proper attitude is maintained.

### Identification of FCMs

The inventory and condition data are stored in a file for each bridge. The file contains previous inspection reports, as-built drawings, repair and maintenance work recommended and performed, and current load rating information. It is recommended that each file be flagged to indicate if this is a fracture critical bridge. Otherwise the inspector may be at the site and ready to work before he realizes that a special level of inspection is necessary. This level of inspection often will require special equipment that must be planned in advance. A qualified structural engineer should identify FCMs. At times a structural analysis may be necessary. The documentation should include critical locations and critical details. Special concerns such as previous damage and repairs should also be noted if these areas warrant special attention. Some FCM bridges are more critical than others because of the number of cycles, type of details, or material. The file should contain all this relevant information so that the level of inspection is appropriate for the bridge.

### Resource Requirements and Implementation

Fracture critical bridge inspections are expensive if done properly. Because the inspector concentrates on critical areas where cracking is most likely to occur, this approach is the most efficient use of resources. Special equipment, such as hydraulic man-lifts or platform devices, may be required to access the critical areas. To supplement this equipment, special manpower support and traffic control may also be required. The bridges should be studied carefully to ensure that the necessary resources are provided. It is also important to ensure that an adequate amount of time is available for the inspection. The quality of inspection must have priority over the quantity, particularly for a fracture critical bridge. It may be helpful to combine inspection teams for optimum efficiency in using the equipment. Special equipment may also be necessary such as NDT devices, special lights, or ventilation devices, particularly for closed boxed girder bridges.

### Quality Control

The final consideration in implementing a fracture critical bridge inspection program is quality control. Quality control is often performed on a hit-or-miss basis. There is rarely a well-defined program. To be useful, it must consist of clearly defined procedures that result in a quantitative measurement of the quality. These procedures should be performed in a standardized way so that they can be compared from team to team and from year to year. Quality control should monitor overall and individual levels of conformance.

## THE FCM BRIDGE INSPECTION

### Preparation

Fracture critical bridge inspection begins before the team arrives at the bridge. The team should study the file carefully while it is still in the office. It is important for each inspector to understand which members are fracture critical and where the fracture critical zones are located. The loading history of the structure is helpful. Fatigue-prone details should also be identified. Records of damage to the structure because of collision or corrosion and repairs are also important. In addition to access equipment, the team may need special tools such as magnifying glasses, spotlights, or dye-penetrate testing kits.

### Assignment of Duties

When more than one person is making the inspection, it is important to coordinate the activities. Considerations should be given to the skills of the individuals making up the team. One person must be in charge. It is the team leader's responsibility to ensure that duplications are minimized and that there are no omissions in inspection of FCMs. Data collection should also be coordinated so that it can be efficiently incorporated into a report.

### Hands-on Inspection

A hands-on inspection should be performed on all of the FCMs. All details identified as prone to cracking must be checked closely. The inspector's eye should be within 24 in. of the surface. The member is viewed from all sides and all angles. The inspector should use additional light and magnification to evaluate the member if necessary. The inspection should begin with a general evaluation of the structure and fracture critical member. It is important to look for things such as misalignment of spans, either horizontally or vertically. Unusual movement or noise might also indicate serious problems. During the overall evaluation, inspectors should also look for distortions or damage created by traffic, flooding, and so on. After the overall evaluation, each member and each detail should be checked closely. The inspector should focus on tension zones of fracture critical members and fracture critical connections. Details that create stress concentration should receive special attention. Examples of details that should be checked closely are

- Intermittent welds between the web and tension flange;
- Areas of sudden change or cross section near the ends or cover plates;
- Locations of stress risers such as nicks, scars, flaws, and holes that have plug welds, irregular weld profiles, and areas where the base metal has been undercut;
- Locations where stiff bracing members of horizontal connection plates are attached to thin webs and girder flanges;
- The web adjacent to a floor beam connection plate;
- Gusset plates, improperly coped members re-entering corners, and the gap between web stiffeners and flanges;
- Longitudinal and vertical stiffener intersections;
- Longitudinal stiffeners that have been connected together with butt welds;
- Location of welds at gusset-transverse-web intersections;
- Flanges that pass through a web, such as girder flange passing through a box girder pier cap;
- Box-beam-to-column intersection; and
- Eyebars.

Discontinuities resulting from in-service problems should also be scrutinized. Examples of these are corrosion, flaws, and welded repairs. Areas where corrosion is likely to give problems are as follows:

- Under deck joints;
- Areas around scuppers and drain pipes;
- Under open steel grates;
- On flat surfaces where debris accumulates;
- On exposed surfaces of fascia members;
- On steel in contact with concrete;
- At overlapping steel plates; and
- At corners of steel angles and channels.

Other special details that should be given attention during the FCM inspection are

- Shear connectors in the negative moment region;
- Pin and hanger assemblies;
- Tack welds on bolted or riveted connections;
- Unfilled holes or holes filled with weld metal;
- Field welds in tension zones; and
- Suspicious attachments making tension zones, such as utility attachments.

## FCM Inspection Report

By definition, fracture critical bridges are those prone to failure that may result in a catastrophe. It is important that the inspection of a fracture critical bridge be documented thoroughly and accurately. This should include a narrative description of all FCMs, whether there are serious problems or not. Photographs and sketches should be included. In cases in which there are many details and findings, tables and charts are also necessary. The data should be organized and cross referenced for efficiency in interpreting the report. The report should provide information on why problems occurred. Repairs are not likely to be effective unless they begin with the cause of the problem. The report should also include conclusions and a summary of the findings. Along with communicating the existing condition, the inspection report should provide an ongoing record of the condition of the bridge and verification of the thoroughness of the inspection activities. Bridges are unquestionably safer because they are inspected. Most deficiencies can then be identified and appropriate remedial actions taken. Occasionally there will be serious flaws that cannot be seen by the inspector. If a fracture occurs, the report can be used to verify that a proper inspection was made.

## What To Do if a Flaw or Crack is Found

It would be difficult to defend a situation in which a bridge failed after the defect had been identified. It is therefore important that the inspector communicates the findings in a timely manner. Ordinarily the inspector would prepare the report and forward it to a supervisor for review. If the supervisor is busy, this may take a week or more. Flaws on fracture critical members should not wait that long for evaluation by an engineer. Some flaws such as a visible crack in a tension flange of a two-girder bridge should be reported immediately. The inspector should go to a phone and call a supervisor. The agency should have an approved procedure for immediate closure if this is warranted. Other problems such as a flaw in a web may be reported when the inspector returns to the office. It is better for the inspector to err on the side of safety. If there is a question about the significance of a finding, an engineer should be contacted as soon as possible. When problems are identified, it is a good idea to go back and look at similar details throughout the bridge. Often inspectors have found cracks at other locations that had already been inspected after finding the first. This demonstrates that it helps to know exactly where to look and what to look for on the other details. After a flaw or crack has been identified, it may be helpful to do additional evaluation with NDT such as dye penetrate, magnetic particles, or ultrasonic or radiographic procedures.

*Publication of this paper sponsored by Committee on Structures Maintenance.*