bridge crossings

ARE YOU SURE THAT'S FRACTURE CRITICAL?

Understanding which steel bridge elements are fracture critical members will provide the required protection while saving on in-service inspection.

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ONE OF THE MOST NOTEWORTHY bridge failures in the United States occurred in 1967, when the Point Pleasant Bridge over the Ohio River (also known as the Silver Bridge) collapsed, resulting in 46 deaths.

The collapse was due to brittle fracture of one of the eyebars that formed the suspension system of the bridge. The subsequent failure investigation revealed that the fracture was due to brittle propagation of a tiny crack in the eyebar. Because the fracture toughness of the eyebar was extremely low, a relatively small crack led to a brittle fracture of the eyebar, which in turn led to the collapse of the bridge.

This collapse was the catalyst for many changes in material specifications, design, fabrication and shop inspection of steel bridges. These requirements are codified in the AASHTO *Bridge Design Specifications* and the AASHTO/AWS D1.5 *Bridge Welding Code* (AWS) and are applied to tension members whose fracture could lead to bridge collapse. (Another bridge incident—the failure of a pin-and-hanger assembly, which triggered the collapse of one span of the Mianus River Bridge in 1983—served as the impetus for enhanced field inspection requirements for these same members.)

The Three-Legged Stool

Today, a total fracture control plan (FCP) is often illustrated as a three-legged stool, where each leg is made up of a part of the plan, as illustrated in Figure 1. (Since the introduction of the FCP, the authors are not aware of any failures in fracture critical members fabricated to the FCP. Hence, the FCP concept appears to be serving its intended purpose.)

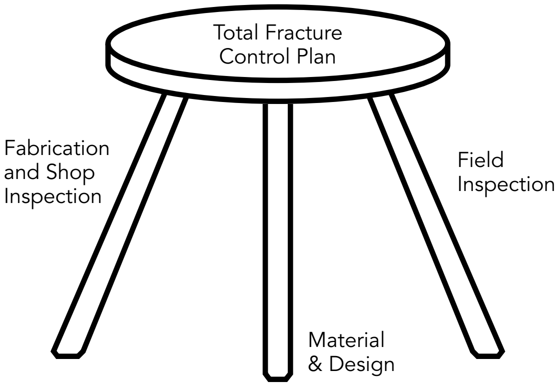

Figure 1 – The three "legs" of a total fracture control plan for bridges.

It is essential to understand that the FCP was specifically developed in response to failures (i.e., brittle fractures) in non-redundant tension members that occurred in the 1970s. Such members, which may be either entirely (e.g., a truss member) or partially (e.g., a flexural member) in tension became known as fracture critical members (FCMs). An FCM is defined by the *Code of Federal Regulations* (23CFR650 – Bridges, Structures and Hydraulics) as "a steel member in tension, or with a tension element, whose failure would probably cause a portion of or the entire bridge to collapse."

Prior to the FCP, the design of tension members was based

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solely upon prevention of yielding; there were minimal requirements on steel toughness (i.e., no Charpy V Notch toughness requirements) and less stringent fabrication and shop inspection requirements. In fact, there was no AWS bridge welding code in existence. Researchers and engineers alike recognized that control of brittle fracture in non-redundant tension members, or portions of members in tension, was important.

In short, the primary objective of the FCP is to prevent brittle fractures of non-redundant tension members and tension components. The material, fabrication and shop inspection portions of the FCP are intended to minimize the frequency and size of discontinuities that might initiate a crack and also to ensure that materials with greater flaw tolerance are used for these members. Arms-length in-service field inspection is intended to discover fatigue cracks before they become a critical size.

Classifying a Member as an FCM

To be classified as an FCM, two basic yet specific criteria must be met:

1. An FCM must be subjected to net tensile stresses from either axial or bending forces. For example, a member that carries 100 kips in dead load compression but 200 kips in live load tension would satisfy this portion of the definition since the *net* force is tension. It is recognized that for brittle fracture to occur and propagate, tensile forces that exceed any compressive forces *must* be present in the member. As another example, in a simple-span beam only the components of the beam in tension (i.e., bottom flange and portion of the web in tension) would meet this requirement.

2. An FCM must be determined to be non-redundant. While definitions vary slightly, the concern is for members whose fracture would result in collapse of the bridge or a portion of the bridge. A member with an alternate load path—i.e., a redundant member—should not be considered fracture critical. Members such as the lower tension chord of a truss, single or double eyebars or pin and link hangers are typically considered as non-redundant members and identified as FCMs because it is presumed that if the member were to fail in brittle fracture, it could trigger the collapse of the bridge. In the absence of a more rigorous system analysis, this is of course a reasonable assumption. It is these types of members that were on the minds of the individuals who developed the FCP. In contrast, however, the tension flanges of multi-girder bridges are not considered FCMs because the adjacent girders provide a redundant load path and load capacity in the event of a fracture of any given girder.

If either of the above criteria is not met, the member shall not be considered an FCM. That is true of every specification in the United States governing steel bridge design, fabrication and in-service inspection that includes the concept of an FCM.

The responsibility to designate a member or member component as an FCM is incumbent on the design engineer. Once it is determined that the element meets both of the above criteria, the member must be clearly labeled as FCM on the design plans. This is essential as it alerts the fabricator to obtain the proper material and fabricate the member to the FCP. However, in addition to the more stringent material and fabrication requirements, the member will also be subject to more rigorous and costly arms-length in-service inspection every two years for a highway bridge.

Applying an FCP

Interestingly, during the development of the FCP, those who crafted the provisions recognized that engineers, given the choice, will often specify the most conservative option provided in a specification and in this case, potentially require the FCP regardless of member loading, type, etc. simply because it would be perceived to be "safer." To avoid this, the commentary to the FCP in AWS explicitly states that it is not intended to be used for members the engineer simply deems "important." In fact, the commentary goes so far as to state that the FCP is not intended to be used for anything but bridges. For example, see this wording from the commentary:

"The fracture control plan should not be used indiscriminately by the designers as a crutch 'to be safe' and to circumvent good engineering practice. Fracture critical classification is not intended for 'important' welds on non-bridge members or ancillary products; rather it is only intended to be for those members whose failure would be expected to result in a catastrophic collapse of the bridge."

Thus, although a member may be deemed "important," if it does not meet the two criteria cited above the member shall not be classified as an FCM. For example, failure of an end-post of a simple span truss will most likely cause collapse of the span. However, since it is never subjected to tension, it would be incorrect to label it as an FCM simply because it is a critical or "important" member in the bridge. This commentary leaves little to interpretation.

Despite the guidance in the specifications, it has become apparent that some design engineers occasionally incorrectly classify steel members as FCMs. This is likely due to inexperience and lack of familiarity with the spirit and objective of the AASHTO/AWS FCP. Nevertheless, in order to properly identify when a member should be classified as an FCM, it is best to first examine the definitions contained in various specifications (underlines are for emphasis):

From AWS:

➤ AASHTO/AWS D1.5 *Bridge Welding Code*, Article 12.2.2–Definitions

"Fracture critical member (FCM). Fracture critical members or member components are tension members or tension components of bending members (including those subject to reversal of stress), the failure of which would be expected to result in collapse of the bridge. The designation 'FCM' shall mean fracture critical member or member component. Members and components that are not subject to tensile stress under any condition of live load shall not be defined as fracture critical."

➤ AASHTO/AWS D1.5 *Bridge Welding Code*, Article C12.2.2–Commentary on Definitions

"Tension members or member components whose failure would not cause collapse of the bridge are not fracture critical. Compression members and portions of bending members in compression may be important to the structural integrity of the bridge, but do not come under the provisions of this plan. Compression components do not fail by fatigue crack initiation and extension, but rather by yielding or buckling."

From the American Railway Engineering and Maintenance-of-Way Association (AREMA):

➤ AREMA *Manual for Railway Engineering*, Chapter 15, Article 9.1.14.2a

"Fracture critical members (FCM) are defined as those tension members or tension components of members whose failure would be expected to result in collapse of the bridge or inability of the bridge to perform its design function. The identification of such components must, of necessity, be the responsibility of the bridge designer since virtually all bridges are inherently complex and the categorization of every bridge and every bridge member is impossible. However, to fall within the fracture critical category, the component must be in tension. Further, a fracture critical member may be either a complete bridge member or it may be a part of a bridge member."

➤ AREMA *Manual for Railway Engineering*,
Chapter 15, Article 9.1.14.2b

"Members or member components whose failure would not cause the bridge to be unserviceable are not considered fracture critical. Compression members and member components in compression may, in themselves, be critical but do not come under the provisions of this Plan. "

As clearly stated in these specifications, compression members or components of members in compression are not to be considered FCM. Both AREMA and AWS use essentially the same definitions and state that compression members "do not" come under the provisions of the FCP. Further, redundant members do not come under the provisions of the FCP. The use of the phrase "do not" also leaves no interpretation and differs from other typical specification type verbiage, such as "should" or "may."

FCM or not?

In the interest of providing guidance, a few typical members found in steel bridges are listed along with basic rationale for either classifying or not classifying the member as an FCM.

Multi-girder bridges and stringers. Bridges with multiple longitudinal members, such as girder bridges with three or more girders or stringer beams of long-span bridges, are examples of members with alternate load paths in the event of a fracture. Their criticality is similar to the bridge deck, where fracture would result in local failure of the deck but not collapse of the bridge. As an example, fatigue cracks were found in late 1970 at cover plate terminations on the Yellow Mill Pond bridge, which carried I-95 in Connecticut. The girders had numerous small cracks and although one girder almost completely fractured, the bridge continued to carry traffic.

While a portion of these members is subjected to tension due to bending, failure of a single stringer or girder would not result in collapse of the bridge or even a part of the roadway. Multiple stringers supported by transverse floor beams are also inherently redundant.

Floor beams. Some engineers have chosen to classify floor beams fracture critical, perhaps in consideration of the support of the roadway. Floor beams should be assessed for FCM status in the same manner as any other bridge member—i.e., is fracturing of a floor beam likely to result in the collapse of the bridge? Regarding roadway support, consider the following:

1. Is the bridge deck composite with the stringers and floor beams? If so, in order for the riding surface to collapse, the entire floor system must suffer a fracture.
2. Are there continuous stringers over the floor beams? Continuous stringers offer an alternate load path for the vehicle load.
3. How are the floor beams framed into the main longitudinal elements? Can a failed floor beam in conjunction with the bridge deck carry load via an arching action spanning across the fracture?
4. Assuming the tension side of the floor beam fails, is it reasonable to assume the entire floor beam would suffer a full-depth fracture?

In most cases, floor beams in conjunction with continuous stringers and the continuity of the deck will provide a redundant system capable of carrying the vehicle load without a collapse.

The authors have observed cases where engineers have classified floor beams as FCMs on bridges where the floor beams are spaced very closely, such as three feet or less. It is difficult to imagine that failure of a floor beam spanning from main girder to main girder spaced so closely could result in collapse of the bridge or roadway. If one were to idealize the main girders as supports between which the floor beams span, the cross section that carries the load would be comprised of multiple girders (i.e., floor beams). Hence, by definition, the floor beams could not be classified as FCMs at such close spacing.

If a floor beam is judged to be fracture critical, only the portion subjected to tensile stresses should be subjected to the FCP. If the floor beam is a rolled beam, while the entire beam would be required to meet the more stringent CVN material requirements, only the portion in tension is subjected to the FCP fabrication and inspection requirements. Hence, welds made to the compression flange would not be subjected to the FCP even though the rolled beam is a single piece of steel. If the floor beam is a fabricated plate girder, the tension flange and the web must meet the more stringent CVN material requirements of the FCP. However, only the portion of the web that is in tension needs to meet the FCP fabrication requirements. The top flange, which is only in compression, would not be considered fracture critical. Also, if the floor beam is designed as a simply supported member, small negative moments that may be produced due to a shear connection at the ends would not justify classifying the top flange as FC material.

Primary longitudinal girders. While the FCP applies to various elements, it was failure in elements such as primary longitudinal girders that led to the development of the plan. The classic main girders of a "two-girder" bridge can reasonably be classified as FCMs since failure of one of the beams may be expected to lead to collapse of the bridge. In the absence of any rigorous system analysis, the portions of the girders subjected to tension (flange and web) would be classified as FCMs and be required to meet the FCP, while the portion of the girder that is only subjected to compression does not, as illustrated in Figure 2.

Tension chords or diagonals in trusses. Generally speaking, most tension diagonals and chords in trusses would be classified as FCMs.

Tie girders. Generally speaking, tension ties would be classified as FCMs.

Miscellaneous attachments to FCMs. In addition to primary members, certain attachments must also be classified as FCMs and be fabricated to the requirements of the FCP. The reason for this is to ensure that components such as longitudinal stiffeners meet the same requirements as the base metal of the primary member. Further, the welds used to attach these components to the primary member must also meet the provisions of the FCP. For example, see this excerpt from AWS Article 12.2.2.2 Attachments:

"Any attachment welded to a tension zone of an FCM member shall be considered an FCM when any dimension of the attachment exceeds 100 mm [4 in.] in the direction parallel to the calculated tensile stress in the FCM. Attachments designated FCM shall meet all requirements of this FCP."

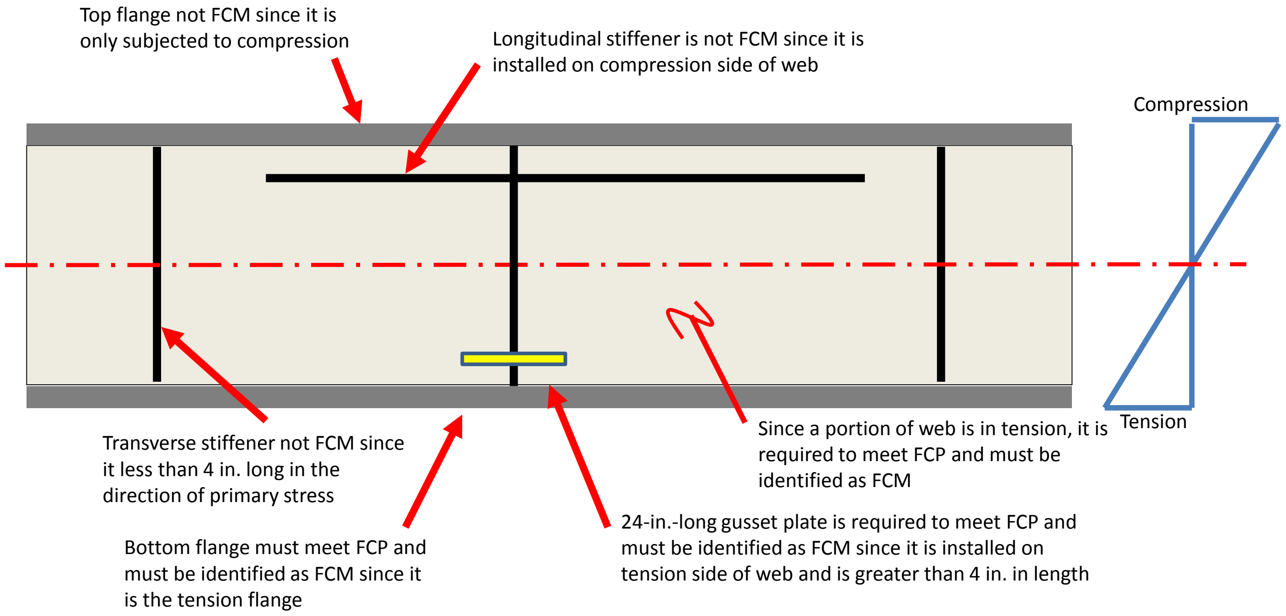
The FCP clearly states the attachment must be located on the portion of the member subjected to *tensile* stresses. Hence, a longitudinal stiffener that is welded to a girder in the tension zone of the web plate must meet the FCP, while a longitudinal stiffener in the compression zone of a web plate does not need to meet the FCP, as shown in Figure 2. Note that even though the attachment is welded to a web plate—which is designated as FCM in terms of the *material* selection (see AWS C12.2.2.2)—due to the fact that a portion of the web is in tension (since the welding of the longitudinal stiffener is on the compression portion of the web) there is no need to invoke the FCP. Note also that short attachments, such as a transverse stiffener, which is always less than 4 in. long in the direction of primary stress, need not be classified as FCM.

Ongoing Research

There are currently several research projects under way focusing on bridges and bridge members traditionally classified as fracture critical. Individual projects are studying the following areas:

Member-level redundancy. This research effort is examining the strength and fatigue performance of both riveted and

Figure 2 – Example of classification of FCM components on a plate girder (created by Robert Connor).



bolted built-up members. While it is accepted that built-up members possess some level of internal redundancy, it has not been fully quantified through large-scale experimental or analytical research. Pooled fund study TPF-5(253) is characterizing this behavior and will result in evaluation and design guidelines for such members to ensure sufficient redundancy exists.

System redundancy. Several studies are under way, such as NCHRP Project 12-87a (research funded by AISC/NSBA focusing on twin-tub girders) as well as research sponsored by other agencies that are working to develop modeling, evaluation and design guidance related to analyzing bridges traditionally classified with FCMs. While it is generally presumed that failure of an FCM will cause collapse of the structure, field experiences where such failures have occurred suggest otherwise in all but extreme cases, such as in the Silver Bridge. These projects will result in rational criteria to characterize the benefits of load redistribution provided by the structural contributions of the deck slab, secondary members, parapets and other components not traditionally used. Further, the minimum live load capacity that is to be maintained in the faulted state will also be defined.

Exploitation of superior-toughness steel. It is well known that modern steels, in particular the HPS grades, offer far superior fracture toughness than "older" steels. However, the current A709 toughness requirements for HPS grade, while good, do not fully exploit the potential benefits of the HPS grades in terms of fracture resistance. These grades are consistently produced with toughness levels that far exceed minimum requirements. The research being conducted through pooled fund study TPF-5(238) explores the benefits of increasing the toughness requirements of some steel grades so that brittle fracture is no more likely than any other limit state, thereby effectively "taking fracture off the table" so to speak. In the extremely unlikely event a fatigue crack were to develop, tolerable crack sizes will be large enough to be reliably detected during normal inspections. By treating brittle fracture like any other limit state (e.g., buckling), it can be effectively mitigated eliminating the need for the term "FCM" in terms of long-term inspection.

Safer Bridges

The AASHTO/AWS D1.5 FCP has been in place for nearly 35 years and appears to have eliminated brittle fractures in steel bridges through improved material toughness, fabrication practices and shop inspection. Additionally, the modern steels, in particular the HPS grades, possess far superior toughness than those used before the introduction of the FCP. The combination of these factors provides much greater safety than our legacy bridges built before the FCP.

While the additional first cost associated with the FCP have been estimated to be 5% to 10% of the total steel fabrication cost, the FCP should not be invoked based on the false assumption that this will somehow make the bridge "better." Designers and owners must appreciate that once a member is classified as an FCM, it is subjected to arms-length biennial inspections for the life of the bridge. As a result, the *long-term* costs associated with inspection greatly increase the life-cycle cost of the structure. When invoked arbitrarily, this simply increases costs, with little or no increase in actual performance of the structures.

In summary, engineers are encouraged to become familiar with the existing AASHTO/AWS D1.5 *Bridge Welding Code* provisions to ensure they are specified only when necessary and appropriate. Doing so will result in the most economical steel structure and is in the best interest of the owner, fabricator and public. Further, as current research progresses and is moved into practice, the meaning of the term fracture critical will certainly evolve. In fact, with modern steels, modern fatigue design approaches and advanced analytical tools, we may see a time when the term fracture critical will no longer be relevant. ■