Guide to Evaluating Details for Susceptibility to Constraint-Induced Fracture

Smarter.
Stronger.
Steel.

Guide to Evaluating Details for Susceptibility to Constraint-Induced Fracture

National Steel Bridge Alliance

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by

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Cover image courtesy of Vince Gastoni, Parsons Corporation.

Preface

This guide explains how to evaluate steel bridge details for susceptibility to constraint-induced fracture (CIF). The guide is directly based on a technical report titled “Evaluation of Steel Bridge Details for Susceptibility to Constraint-Induced Fracture,” Report No. FHWA-HIF-21-046, published by the U.S. Department of Transportation (US DOT), Federal Highway Administration (FHWA), in September of 2021. In fact, most of the content of this guide is directly copied from that report, with minor editorial changes made to facilitate formatting and flow of the guide. In addition, direct statements were added regarding when the use of specific problematic details is not recommended. Significant portions of the FHWA report were omitted from this guide for brevity; readers interested in further information on the concepts of ductility and fracture and other background material can read the full FHWA report, which is available for free download from the FHWA website.

First-time readers of this guide are encouraged to review Chapters 1, 2, 3, and 4, which provide a general overview of ductility and fracture and a simple procedure for evaluating steel bridge details for susceptibility to CIF. Afterwards, readers can review individual example evaluations in Chapters 5, 6, 7, and 8 as appropriate for their needs. Chapter 9 provides suggestions for mitigating conditions of elevated susceptibility to CIF.

Although this guide is based heavily on the above-cited FHWA report, the recommendations in this guide do not in any way reflect the opinions, policy, recommendations, or other statements of the FWHA.

Domenic Coletti, PE

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CHAPTER 1 - EXECUTIVE SUMMARY

Historically, reports of significant problems associated with details featuring intersecting welds in steel bridges have been rare. However, there have been several notable cases involving constraint-induced fracture (CIF). CIF is a particular concern since it can occur in a brittle fashion, suddenly and without warning (different from other types of problems such as corrosion or fatigue crack growth, for example). CIF generally occurs in details that feature a high degree of constraint (leading to a high level of stress triaxiality), in combination with high levels of tensile stress (including residual stresses) and a notch-like or crack-like planar discontinuity approximately perpendicular to the primary flow of tensile stress. Details subjected to a high degree of constraint often feature the intersection of two or three welded structural steel elements. The distinction between “intersecting welds” and “constraint resulting from the intersection of welded structural elements” is important.

Bridges featuring certain types of details with intersecting welded steel elements may be subjected to an increased susceptibility to CIF. In extreme cases, details with high degrees of triaxial constraint and crack-like or notch-like planar discontinuities have experienced sudden, severe fractures, resulting in bridge closures and emergency repairs. There have been several cases of CIF in bridges in the United States, including most notably the Hoan Bridge fracture in Wisconsin on December 13, 2000. In the case of the Hoan Bridge, CIF occurred after the bridge had been in service for over 25 years and resulted in the nearly full-depth fracture of two of the three main girders in one of the approach spans. This prompted immediate closure and emergency repair of the bridge, which carries six lanes of interstate highway traffic and nearly suffered a catastrophic collapse. The steel in the girders exhibited reasonable toughness with no evidence of fatigue cracking prior to the CIF event, and it was also concluded that low temperatures at the time did not cause the initiation of fracture (but did reduce the ability of the structure to arrest dynamic crack growth).

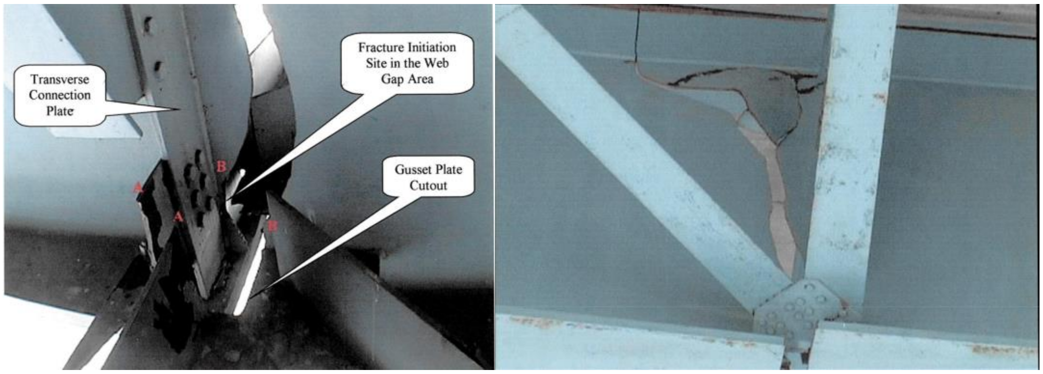


Figure 1. Hoan Bridge fracture initiation site.

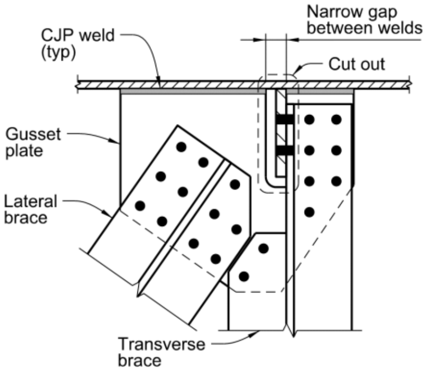


Figure 2. Plan view of Hoan Bridge bracing node connection detail, fracture initiation site.

Since the Hoan Bridge fracture, research has improved the general understanding of CIF. To provide a better understanding among designers and bridge owners of constraint, CIF, and proper detailing of steel bridges with welded elements, the Federal Highway Administration (FHWA) sponsored the creation of this report. The report is based on a review of current research and practices and the input of a panel of steel-bridge industry experts, including academic researchers, bridge design engineers, steel bridge fabricators, and bridge owners.

The findings in this report are:

- Steel bridge details featuring intersecting welds are not necessarily subject to an elevated susceptibility to CIF.
- Three conditions typically contribute to elevated susceptibility of steel bridge details to CIF: a high net tensile stress, a high degree of constraint, and a planar discontinuity approximately perpendicular to the primary flow of tensile stress.
- Evaluating details with respect to criteria rooted in a technical understanding of CIF can help bridge owners identify details that are candidates for redesign and retrofit.
- Retrofitting and redesigning details with intersecting welds without proper understanding of CIF can lead owners to undertake design and/or retrofit strategies that may result in poorer, not better, performance.

CHAPTER 2 - TERMINOLOGY

2.1 INTERSECTING WELDS

The American Welding Society (AWS) specifications such as the voluntary AWS A3.0 (AWS, 2010), the voluntary AWS D1.1 (AWS, 2015), and the binding AASHTO/AWS D1.5 (AASHTO/AWS, 2015) (23 CFR 625.4(d)(1)(vii)) do not describe "intersecting welds," but a variety of descriptions of the term "intersecting welds" are presented in other bridge design and bridge inspection practice documents. These descriptions are typically provided in the context of classification of "problematic details," "details susceptible to fatigue," or "details susceptible to fracture."

Perhaps the most common description takes a form similar to this: "welds that run through each other, overlap, touch, or have a gap between their toes of less than ¼ inch" (Ryan et al., 2010). However, this description can be misunderstood when used in the context of evaluating whether a given detail may or may not be problematic. The inclusion of the measurement of "a gap between their toes of less than ¼ inch" implies there is a measurable criterion for characterizing whether a detail has "intersecting welds." Such a criterion, on its own, typically is insufficient for evaluating the susceptibility of a detail to CIF.

Such descriptions might lead an engineer to believe that details with welds that run through each other, overlap, or touch are problematic, and that the introduction of a gap between weld toes of at least ¼ inch should alleviate the situation. However, consider the example of the intersection of flange-to-web fillet welds with a complete joint penetration (CJP) groove weld in a butt joint for a flange or web shop splice. Such a detail would fall under the above-cited description of "intersecting welds." Yet, these types of details have been used extensively in steel bridge fabrication without concerns or reported problems.

To more clearly separate "intersecting welds" from "details subject to an elevated susceptibility to CIF," it would be helpful to consider the term "intersecting welds" as only identifying a condition where welds run through each other, overlap, or touch. The term "constraint-relief gaps" (i.e., the "gap between [weld] toes," or "web gap"), including their measurement and their effect on performance, can then be differentiated from the term "intersecting welds" and instead used as part of a more comprehensive evaluation of details for susceptibility to CIF.

To more explicitly identify the geometry of these types of details, the following terminology is used in this report:

> ***Intersecting welds:*** Welds that run across each other, overlap, or touch.

See Figure 18 and Figure 19 for illustrations of one example of a detail with intersecting welds.

Note that the presence of intersecting welds in and of themselves does not necessarily represent the presence of a problematic detail.

2.2 CONSTRAINT-RELIEF GAPS

In previous literature related to CIF, the words "web gap" and "gap between weld toes" were used to denote gaps provided in one element welded to and constraining another element; these gaps are intended to provide relief from triaxial constraint in the constrained element, enabling that element to yield. However, these descriptive terms, which are not binding under FHWA regulations, can be the subject of various interpretations, which might lead to confusion.

A common historical example of this type of constraint-relieving gap is an interruption in a longitudinal stiffener welded to a girder web at the intersection with a vertical stiffener welded to the same web, where the gap in the stiffener is measured at the web (hence the historical term "web gap"). See Figure 3 for an illustration; the dimension in the figure denoted as the “constraint-relief gap” (a term described later in this report) is the “web gap.” Note that the type of detailing shown in this figure is not recommended and can potentially exhibit elevated susceptibility to CIF (as explained later in this report) and poor fatigue performance, but may be found in older structures. This so-called “web gap” provides the web with relief from triaxial constraint. However, the term “web gap” has been described as confusing by some, and historically different dimensions have been used.

Furthermore, a more general term would be useful since providing these types of gaps may be beneficial in details other than longitudinal web stiffeners. For the purposes of this report, the term “constraint-relief gap” is used. A constraint-relief gap is an interruption in a welded structural element to provide some measure of relief from triaxial-constraint induced by that element on an attached element. To properly provide relief from triaxial constraint, the gap provided in a constraint-relief gap should be a “clear” gap; as such, it has traditionally been measured as the gap between the toes and/or ends of the welds connecting the constraining element(s) to the constrained element.

To more explicitly identify the geometry of these types of details, the following terminology is used in this report:

> ***Constraint-relief gap:*** An interruption, of sufficient size, provided in a welded structural element, or its connection to a constrained element, to provide localized relief from constraint induced by that element on a constrained element to which it is attached, so that local yielding can occur.
>
> The dimension describing the size of a constraint-relief gap is measured between the toes and/or ends of the welds attaching the constraining element to the connected, constrained element.

See Figure 3 for an illustration of a constraint-relief gap.

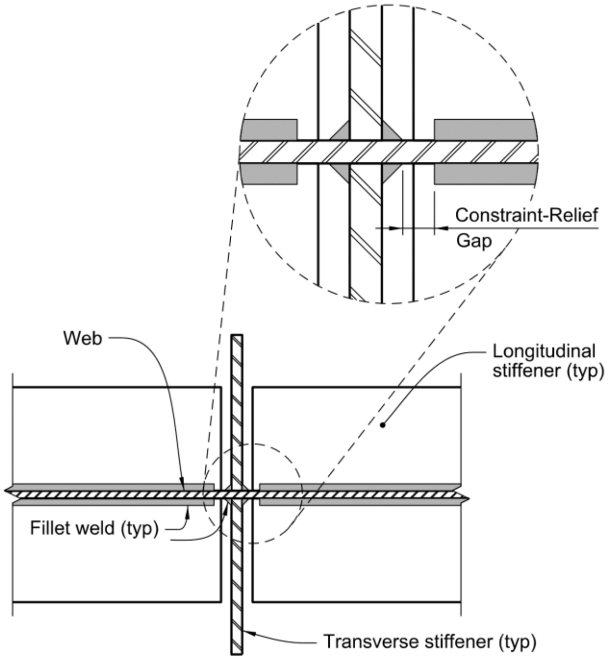


Figure 3. Plan view of girder web with attached transverse and longitudinal stiffeners.

2.3 LIST OF TERMS

This section provides a list of terms used in this report. Unless otherwise specified, the following terms are not binding under FHWA regulations.

Bearing stiffener: An angle or angles, or a plate or plates, attached to a web of a beam or girder to distribute a bearing reaction or a concentrated load into the web over the height of the stiffeners.

Constraint-induced fracture (CIF): “A type of fracture attributed to local constraint conditions in steel under tension, which may occur at details of certain geometries.” (Russo et al., 2016)

Constraint-relief gap: An interruption, of sufficient size, provided in a welded structural element, or its connection to a constrained element, to provide relief from constraint induced by that element on a constrained element to which it is attached, so that local yielding can occur.

Clip: See *cope*.

Cope: A cutout in a structural steel member to avoid physical conflict with part of another element. Also known as a snipe or clip.

Crack: A fracture-type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement.

Crack-like Geometry: A geometric condition in a steel structure featuring a discontinuity in an element, in which the discontinuity has very sharp tips that would be expected to introduce very significant stress concentrations.

Fracture: A partial or total severing of a continuous steel element under the action of force, particularly a tensile force, without prior yielding or deformation.

Intersecting welds: Welds that run across each other, overlap, or touch.

Lateral connection plate: A plate used to interconnect lateral bracing members for attachment to a flexural member (such as a girder).

Longitudinal web stiffener: A stiffener, oriented in a direction at least approximately parallel to the primary flow of axial or flexural stress, attached to a component plate of a member to provide additional local and overall compressive resistance of that component.

Notch-like Geometry: A geometric condition in a steel structure featuring a discontinuity in an element, in which the discontinuity may not have very sharp tips, but in which the discontinuity is nonetheless relatively narrow and the tips would still be expected to introduce significant stress concentrations.

Planar Discontinuity: A geometric condition in a steel structure taking the form of a plane of discontinuity in an otherwise continuous structural steel element, typically featuring a crack-like or notch-like geometry. See also *crack-like geometry* and *notch-like geometry*.

Snipe: See *cope*.

Stiffener: A member, usually an angle or plate, attached to a plate or web of a beam or girder to distribute load, to transfer shear, or to prevent buckling of the member to which it is attached.

Stress Triaxiality: “The ratio of the state of stress a material undergoes to the stress that contributes to yielding” (Schafer, 2000).

Transverse connection plate: A vertical stiffener attached to a beam or girder to which a cross-frame, diaphragm, floor beam, or stringer is connected.

Transverse stiffener: A stiffener attached to a component plate approximately perpendicular to the longitudinal axis of the member to provide additional shear or axial compressive resistance.

Web gap: A particular type of constraint-relief gap, specifically in an element attached to, and otherwise constraining, the web of a flexurally or axially loaded steel member.

CHAPTER 3 - STRESS TRIAXIALITY, CONSTRAINT, AND SUSCEPTIBILITY TO CIF

3.1 FUNDAMENTAL PRINCIPLES OF DUCTILE BEHAVIOR OF STEEL STRUCTURES AND THE EFFECTS OF CONSTRAINT AND STRESS TRIAXIALITY

While it has often been said that steel is an inherently ductile material, that ductile nature can be compromised if a structure is detailed in manner that inhibits the typical uniaxial stress-strain behavior of the material. Clarification of this concept is instructive in understanding the nature and causes of CIF.

The basis for most statements about the inherent ductility of steel is the nature and shape of the basic stress-strain curve of the material, as established by uniaxially loaded tensile specimens. The stress-strain curve for steels generally exhibits a region of significant plastic deformation prior to rupture or fracture. Bridge steels with a minimum specified yield stress of 70 ksi or less (typically 36, 50, and 70 ksi) generally exhibit a defined yield plateau (see Figure 4 for a stress-strain curve generally representative of this type of behavior). The stress-strain curve for Grade HPS 100W bridge steel (which has a yield stress of 100 ksi), does not display a clearly defined yield plateau (see Figure 5 for a stress-strain curve generally representative of this type of behavior), but does exhibit significant plastic deformation prior to rupture.

Figure 4 and Figure 5 show that significant plastic deformation may occur under loading between the uniaxial yield stress, F_y, and the ultimate tensile strength of the material, F_u, with further deformation occurring prior to rupture. This plastic behavior generally results in significant structural deformation prior to reaching the ultimate tensile strength of the material, providing warning of an impending failure. This is generally characterized as “ductile behavior;” that is, the material displays significant ductility prior to failure.

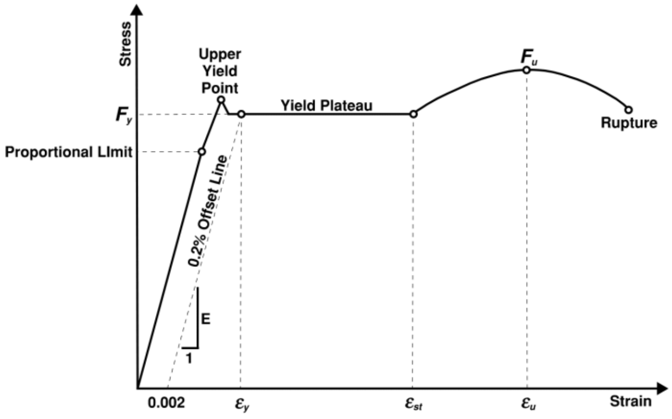


Figure 4. Engineering tensile stress versus strain curve for structural steel with a defined yield plateau.

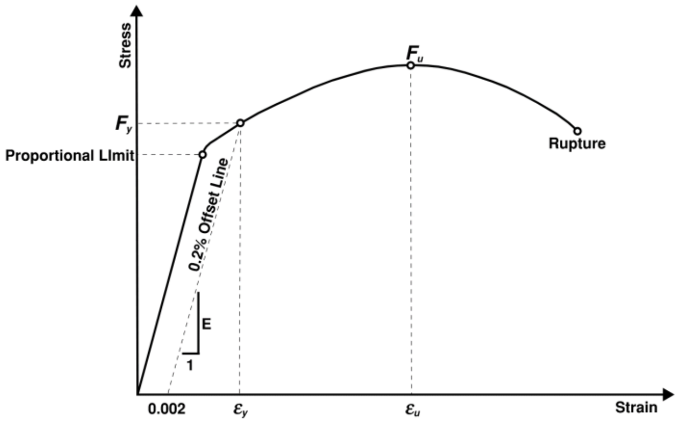


Figure 5. Engineering stress versus strain curve for structural steels without a defined yield plateau.

This type of ductile behavior of steel materials depends on a variety of presumptions, including the application of uniaxial loading at a slow loading rate and the absence of significant residual stresses and stress concentrations. Furthermore, unaxial loading, by its nature, involves the application of stress in only one direction. If the configuration and loading of the structure result in the application of stresses in more than one direction, a biaxial or triaxial state of stress would exist. In that case, the material would exhibit different behavior. In particular, in the case of a triaxial state of stress, the material can be prevented from plastically deforming (yielding). In such cases, the material can be subjected to a tensile stress equal to the rupture stress without having yielded. The presence of residual stresses and/or stress concentrations, especially extremely high stress concentrations resulting from notch-like or crack-like planar discontinuities, can also produce highly localized tensile stresses, exacerbating the situation. The result can be a sudden, brittle failure by fracture. This type of failure is commonly called CIF.

3.1.1 Illustrations of Ductility via Mohr's Circle of Stress

To better understand this concept, it is helpful to review Mohr's circle of stress and the basic concepts of ductility.

It has long been known that to achieve plastic deformation (yielding) of metal materials, the materials have to be able to experience shear stresses and the ability to deform along shear planes. For example, Gensamer (1941) stated, "This is an important concept and needs to be emphasized: no shear stress, no plastic deformation or flow." At a more fundamental level Bruneau et al. (1998) explain, "Steel is a polycrystalline material, that, when loaded beyond its elastic limit, develops slip planes at 45 degrees. These visible yield lines, also known as Lüder lines, are a consequence of the development of slip planes within the material as yielding develops." In other words, shear stresses are associated with yielding. Conversely, if the development of shear stresses is somehow prevented, then yielding cannot occur and the failure mode changes to rupture without any prior measurable ductility.

Implicit in these statements is that the metallic element is free from triaxial constraint, so as to allow the development of the shear stresses essential for yielding. The underlying concepts associated with this statement can be illustrated via Mohr's circle of stress, which is used below to illustrate the effects of constraint on the behavior of a steel element subjected to an axial tension stress.

Consider a typical steel tension test coupon. When subjected to a uniaxial tension stress, with the orthogonal stresses equal to zero, Mohr's circle of stress for an element stressed like a test coupon can be drawn as shown in Figure 6. The stress in the x-direction, σ_x, is the applied uniaxial tension stress. The stress in the y-direction, σ_y, is zero, since there is no applied orthogonal stress or constraint. There is also a shear stress occurring in the material, $\sigma_{x\text{-}y}$, as is demonstrated when the statics of a discrete element in the test coupon are evaluated. As an aside, these concepts form the basis of the Von Mises and Tresca yield criteria.

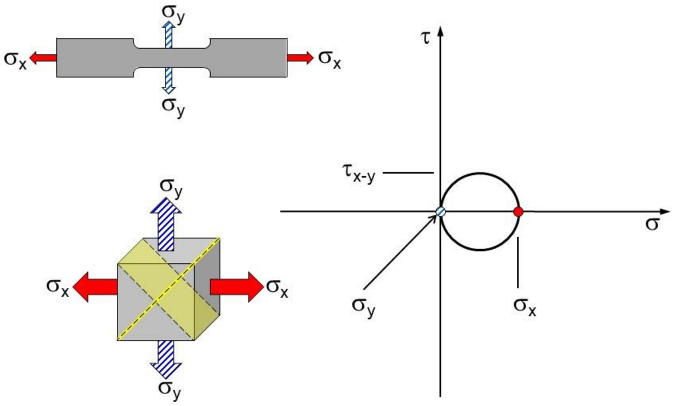


Figure 6. Mohr's circle of stress for a uniaxial test coupon with stress in the x-direction and zero stress in y-direction (modified by the authors; labels added to stress arrows and graph axes).

Similar Mohr's circles of stress can be drawn considering the stresses in the x- and z-directions, and considering the y- and z-directions. All three Mohr's circles of stress (the x- and y-directions, the x- and z-directions, and the y- and z-directions) can be drawn together, noting that σ_y and σ_z are both still zero. Shear is present on two sets of shear planes $\tau_{x\text{-}y}$, and $\tau_{x\text{-}z}$). See Figure 7.

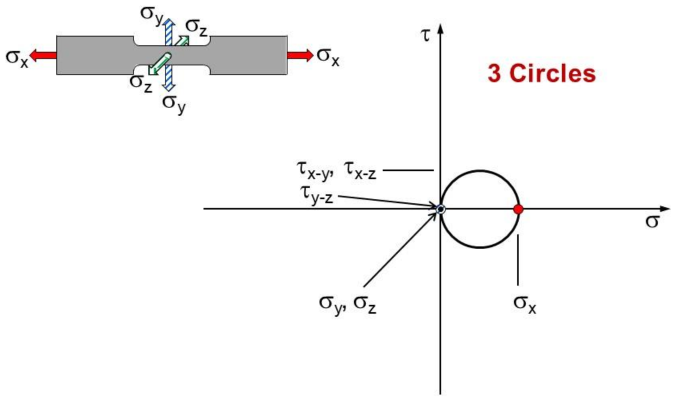


Figure 7. The three Mohr's circles of stress for a uniaxial test coupon with stress in the x-direction and zero stress in the y- and z-directions (modified by the authors; labels added to stress arrows and graph axes).

With this as a basis, it can be seen that as the uniaxial tension stress, σ_x, is increased from σ_{x1} to σ_{x2}, while σ_y and σ_z are both still zero, the associated shear stresses, $\tau_{x\text{-}y}$ and $\tau_{x\text{-}z}$, also increase proportionally. See Figure 8.

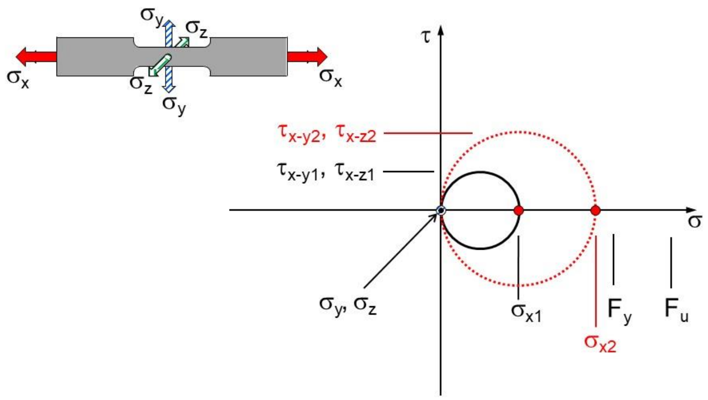


Figure 8. The three Mohr's circles of stress for a uniaxial test coupon, with higher uniaxial stress (modified by the authors; circle colors changed and labels added to stress arrows and graph axes).

3.1.1.1 Illustrations of Ductile Behavior

When the uniaxial stress, σ_x, is increased to a level greater than the uniaxial yield stress of the material, F_y, shear deformations occur in association with plastic axial deformation. The shear strength of the material in this case can be identified as the shear stress associated with the uniaxial yield stress. This is the "critical shear stress" – the shear stress associated with initiation of slip along the shear plane. The critical shear stress is the shear stress occurring in a uniaxial tension test when loaded to the tension yield stress. In the case of an applied uniaxial stress, this shear plane is oriented 45 degrees from the direction of the applied uniaxial stress. See Figure 9.

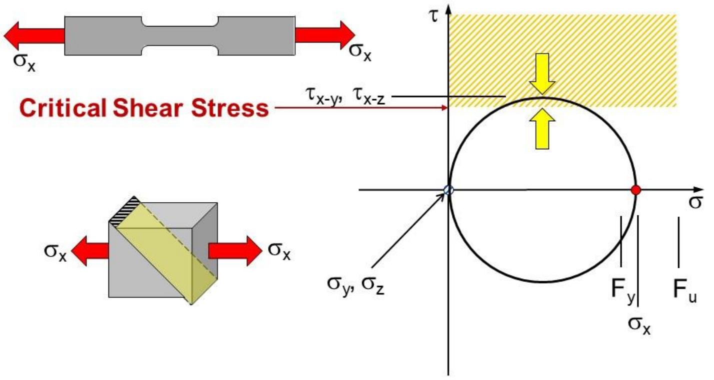


Figure 9. The three Mohr's circles of stress for a uniaxial test coupon, showing the shear strength of the material as related to the uniaxial yield stress (modified by the authors; labels added to stress arrows and graph axes).

3.1.1.2 Illustrations of Non-Ductile Behavior

Consider a case where equal tension stresses are applied in all three orthogonal directions (i.e., the x-, y-, and z-directions), $\sigma_{x1} = \sigma_{y1} = \sigma_{z1}$, a hydrostatic state of tension. Following the principles of statics and Mohr's circle of stress, the resulting three Mohr's circles of stress converge to a single dot and the associated shear stresses are zero. To place this in the context of a real-world situation, consider an element subjected to a tension stress, such as the portion of the web near the tension flange of a steel plate girder subjected to major-axis bending. In such a situation, the x-direction stress would be the major-axis bending stress in web. Now imagine that a vertical stiffener is welded to the web, restraining the web locally in the vertical direction. Assume the vertical stiffener prevents the web from contracting vertically if the x-direction stress in the web exceeds the yield stress; the vertical stiffener represents a vertical constraint on the web and generates a y-direction tension stress when the web tries to yield. Next, also imagine that a longitudinally oriented lateral bracing gusset plate is also welded to the web at the same location as the vertical stiffener. Assume the web, vertical stiffener, and gusset plate are all welded to each other without constraint-relief gaps, that lateral bracing members are attached to the gusset plate, and that cross-frame members are attached to the vertical stiffener. The gusset plate prevents through-thickness yielding of the web; the gusset plate represents a horizontal constraint on the web and generates a z-direction tension stress when the web tries to yield.

The orthogonal tension stresses could be increased from the material's uniaxial yield stress, $\sigma_{x2} = \sigma_{y2} = \sigma_{z2} = F_y$, to the ultimate tensile strength of the material, $\sigma_{x3} = \sigma_{y3} = \sigma_{z3} = F_u$, and the associated shear stresses would still be zero. Since there are no shear stresses, there would be no slip along the shear planes, and thus no deformation. In other words, although the test coupon has been stressed beyond the material's uniaxial yield stress, it still has not experienced any plastic deformation; the test coupon could be at the point of rupture and still not yet exhibit any plastic deformation. In a case like this, the fracture would be sudden and brittle. In conceptual terms, this is similar to the Hoan Bridge detail that suffered from CIF. See Figure 10.

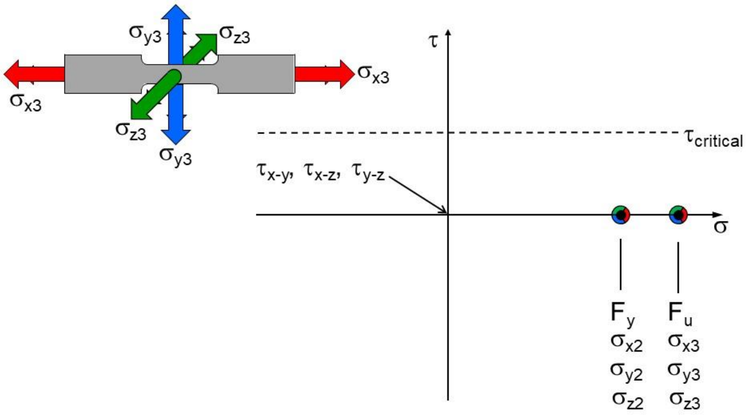


Figure 10. The three Mohr's circles of stress for a test coupon with tensile stresses in all three orthogonal directions all equal to the material's ultimate tensile strength (modified by the authors; labels added to stress arrows and graph axes).

Figure 10 represents an extreme situation, where the three orthogonal stresses are all increased simultaneously and uniformly to the material's ultimate tensile strength. But similar behavior can occur in less severe cases. Consider a case where the axial tension stress in the x-direction is equal to the material's uniaxial yield stress, with orthogonal tension stresses less than the material's uniaxial yield stress in the y- and z-directions. It can be seen that shear stresses, τ_{x-y} and τ_{x-z}, exist, but that they are of lesser magnitude than they would be if the orthogonal tension stresses, σ_y and σ_z, were zero. In this situation, the x-direction tension stress is equal to the material's uniaxial yield stress, but since the shear stresses are less than the critical shear strength, the test coupon would not exhibit plastic deformation.

If the orthogonal tension stresses in the y- and z-directions stay the same, but the tension stress in the x-direction is increased to the material's ultimate tensile strength, the associated shear stresses would proportionally increase. But depending on the specific magnitudes of the various stresses, it is entirely possible that the shear stresses could still be less than the critical shear stress, and thus, there would still not be any plastic deformation. This means that although the test coupon had been stressed beyond the material's uniaxial yield stress, it still had not experienced any plastic deformation; in fact, if the test coupon were at the point of rupture, it still might not exhibit plastic deformation. In a case such as this, fracture would be sudden and brittle. See Figure 11.

These illustrations demonstrate the inherent connection between shear stresses and deformations. This demonstrates that while steel is a material that can exhibit ductility, such behavior is not guaranteed under all circumstances. Furthermore, these illustrations show the link between constraint and fracture. Specifically, when a structural steel element is subjected to triaxial constraint, it can be loaded to a level of stress greater than its uniaxial yield strength and undergo fracture without first experiencing plastic deformation. Figure 10 and Figure 11 illustrate cases where a detail subjected to triaxial constraint could be subject to an elevated susceptibility to CIF.

A more desirable outcome would be for yielding to occur prior to fracture. When a material yields locally, the stress is redistributed to adjacent material and the stress in the yielded section does not immediately continue to elevate to the rupture strength of the material. In addition, in many cases, the plastic deformation associated with yielding is visible and provides an indication of a problem prior to fracture.

Other factors contribute to the ability of a steel structural element to demonstrate ductile or brittle behavior. For example, the inherent toughness of the steel material (i.e., the ability of the material to absorb energy and deform plastically without fracture) affects the material's ductility – tougher steel is more resistant to fracture. Similarly, the temperature of the steel also affects its toughness – the colder the temperatures, the lower the toughness of the material and the less resistant the material becomes to fracture. In older steel bridges, lower toughness steel may naturally be more susceptible to fracture, particularly in low-temperature conditions.

The effects of material toughness and service temperature on the ductility of steel bridges are well-known and have largely been addressed by owners with regard to how they treat older existing bridges and with regard to the design and fabrication of new bridges. However, CIF has occurred in bridges fabricated from steels with good toughness, and has occurred under warm temperature conditions. Good toughness and warm temperatures do not eliminate susceptibility to CIF.

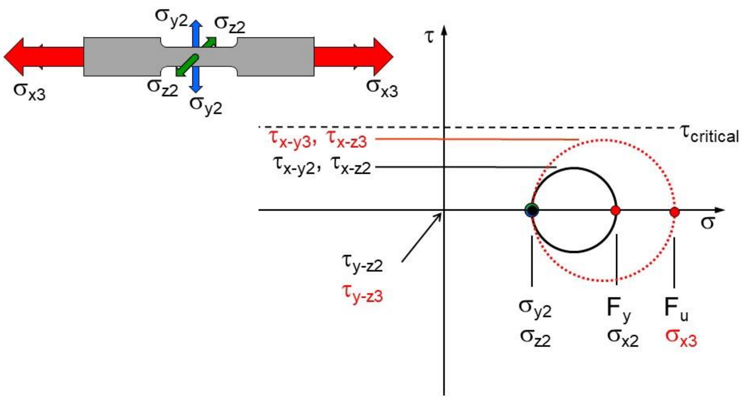


Figure 11. The three Mohr's circles of stress for a test coupon with tensile stresses in all three orthogonal directions, with x-direction stress equal to ultimate strength (modified by the authors; labels added to stress arrows and graph axes).

3.2 THE THREE CONDITIONS CONTRIBUTING TO ELEVATED SUSCEPTIBILITY TO CIF

The existence of constraint alone, even triaxial constraint, in a given welded steel detail does not necessarily equate to an elevated susceptibility to CIF.

Connor and Lloyd (2017) describe three conditions that contribute to the susceptibility of a detail to CIF:

1. "There must be an elevated level of tensile residual stress locked into the local area. While the dominating contribution is residual stresses from welding, other factors contribute to a lesser degree, such as dead load and erection stress. As is well documented, residual stresses due to welding can easily reach the yield strength of the base metal.
2. "The joint must be highly constrained, resulting in a three-dimensional state of stress that prevents plastic flow, as would [otherwise] occur in a simple uniaxial stress state.
3. "Localized area of stress concentration that intensifies dead load and live load stress level."

Any one of these conditions, taken to extreme limits, could lead to adverse performance or even failure of a structural steel element. However, under normal circumstances, any one of these conditions acting alone, or even any two acting together, likely would not lead to an elevated susceptibility to CIF. Instead, it is the occurrence of all three conditions acting together that typically contributes to an elevated susceptibility. The three conditions are discussed below in the order in which they are most likely to occur in typical steel girder bridges.

Section 4.1 discusses how to apply an understanding of these conditions as part of a screening process to evaluate details for an elevated susceptibility to CIF. Chapters 5, 6, 7, and 8 illustrate various examples of the use of this process to evaluate common details for susceptibility to CIF.

CHAPTER 4 - EVALUATING DETAILS FOR SUSCEPTIBILITY TO CIF

4.1 GENERAL CIF EVALUATION PROCEDURE

As described in Section 3.2, three conditions contribute to an elevated susceptibility to CIF, specifically:

1. a sufficiently high net tensile stress, including consideration of residual stresses;
2. a high degree of constraint, preventing local yielding; and
3. a planar discontinuity approximately perpendicular to the primary flow of tensile stress.

Following is a discussion of each condition in detail:

As discussed in Section 3.3.1 of Coletti et al. (2021) , residual stresses are present in all structural steel elements but it is impractical to quantitatively determine their distribution and magnitude outside of the academic research setting, so it is reasonable to assume that the first condition, *a sufficiently high net tensile stress, including consideration of residual stresses*, is present in any and all members or components subjected to a tensile stress or stress reversal. As previously discussed, virtually all structural steel members are subject to some level of residual stress. Residual stresses include both regions of tensile and compressive stresses, which are always in static equilibrium (i.e., the sum of the resultant tensile and compressive forces equals zero), and the magnitude of residual tensile stresses can potentially exceed the uniaxial yield stress of the material. Theoretically, residual stresses can be quantified, but it is impractical to try to do so outside of the academic research environment. So, for the purposes of evaluating a given detail for susceptibility to CIF, a high level of tensile stress can be assumed to exist whenever that given element is subjected to a net applied tensile stress or stress reversal.

The second condition, *a high degree of constraint, preventing local yielding*, is a function of the specific geometry of a given detail. Most structural steel elements in transportation structures are typically relatively thin, such as girder web plates, stiffeners, diaphragms, cross-frame members, and the like. Relatively thin steel elements, on their own, are not subject to a high degree of constraint and typically can yield when stressed to their yield stress. However, when several such elements are assembled together as they typically are in a steel bridge, there can be many locations where one or more elements constrain other elements. The Mohr's circle illustrations presented in Section 3.1 show that a steel element deforms when a uniaxial tensile stress equal to the yield stress of the material is applied, but that yielding of the material is prevented if orthogonal tensile stresses are introduced, restraining shear deformations. For example, the "Hoan Bridge Detail" featured the intersection of three welded structural steel plates (the girder web, vertically oriented connection plates, and longitudinally oriented gusset plates), with attached structural elements (bracing members). The girder web was severely constrained and could not yield locally. This condition, combined with a sufficiently high net tensile stress (including consideration of residual stresses) and a crack-like planar discontinuity approximately perpendicular to the primary flow of tensile stress (discussed below), led to elevated susceptibility to CIF.

Any structural steel detail can be evaluated to determine whether it may be subject to a high degree of constraint. As discussed in Section 3.2 of Coletti et al. (2021), the degree of stress triaxiality can be quantified, but trying to do so in a design environment is impractical due to the difficulty associated with quantifying the magnitude of residual stresses and the degree of constraint provided by various attached elements. However, the evaluation need not be quantitative - a qualitative evaluation is technically sufficient. If a given structural steel detail is configured such that the various elements may provide constraint, relatively simple steps can typically be taken to reconfigure the detail such that sufficient relief is provided to allow for local yielding.

The third condition, *a planar discontinuity approximately perpendicular to the primary flow of tensile stress*, is similarly a function of the specific geometry of a given detail. This type of condition, specifically when it exhibits a "crack-like" or "notch-like" geometry, provides both a stress concentration and a crack initiator. The crack-like or notch-like geometry can existing in a number of different forms, including narrow gaps in longitudinal attachments, weld discontinuities, or similar items. The key is that a plane of discontinuity approximately perpendicular to the primary flow of tensile stress represents a potential problem, whereas a plane of discontinuity parallel to the primary flow of tensile stress does not.

To understand the concept of a planar discontinuity, consider first the term "plane." For the purposes of this report, a "plane" is defined as "a surface in which if any two points are chosen a straight line joining them lies wholly in that surface" (Merriam-Webster, 2021). An ideal plane has two measurable dimensions, while the third dimension measures as zero; in other words, a plane would have a measurable width and length, but no thickness. For the purposes of evaluating susceptibility to CIF, a "planar discontinuity" is a discontinuity in a structure that takes the form of a plane. Theoretically, a planar discontinuity might have zero "thickness" (zero gap between the discontinuous structural elements), but planar discontinuities generally have some measurable thickness (some measurable gap between the discontinuous structural elements).

A classic example of a planar discontinuity approximately perpendicular to the primary flow of tensile stress would be the interruption of a longitudinal web stiffener attached to a girder web in a region where the web is subjected to tension or stress reversal. In some existing structures, such a discontinuity might occur at a location where a longitudinal web stiffener is interrupted to avoid conflict with a transverse web stiffener. The "plane" associated with the planar discontinuity is the plane formed by the end of the longitudinal stiffener; this plane has a width (the width of the longitudinal stiffener) and a height (the thickness of the longitudinal stiffener), and is oriented approximately perpendicular to the longitudinal axis of the girder, and thus perpendicular to the primary flow of tensile stress along the length of the girder in the tension flange, web, and longitudinal stiffener. As can be seen in Figure 16 (and the associated discussion in Section 4.1), such a discontinuity interrupts the flow of tensile stress in the longitudinal stiffener, and concentrates that stress in the web.

If such a planar discontinuity is very "thin" (i.e., if there is a very small gap between the discontinuous structural elements, in this case between the end of the longitudinal web stiffener and the face of the transverse web stiffener), it might represent a crack-like or notch-like feature. The presence of such a crack-like or notch-like planar discontinuity approximately perpendicular to the primary flow of tensile stress would contribute to an elevated susceptibility to CIF; the tension would act to open the discontinuity further and there would be stress concentrations at the end of the discontinuity. However, if the gap between the discontinuous structural elements is wide, it might represent an adequately sized "constraint-relief gap," which would reduce susceptibility to CIF. See Section 2.2 for detailed discussion of constraint-relief gaps; in this case the constraint-relief gap would be the gap between the ends of the longitudinal stiffener-to-web fillet welds and the toes of the transverse stiffener-to-web fillet welds.

For example, consider the detail shown in Figure 12. This figure shows a plan view of a steel girder web with transverse web stiffeners (vertical stiffeners) and longitudinal web stiffeners. In this case, the longitudinal web stiffeners are interrupted at the transverse web stiffeners, with a small gap between the ends of the longitudinal web stiffeners and the transverse web stiffeners. The gaps represent discontinuities in the longitudinal web stiffeners; longitudinal stress in the longitudinal web stiffeners cannot flow across the gap and instead transitions into the web at the gaps. The gaps thus represent a plane of discontinuity approximately perpendicular to the primary flow of stress, with stress concentrations at the points where the ends of the longitudinal stiffeners are attached to the girder web. For the purposes of this discussion, imagine that the web and the longitudinal web stiffeners are subjected to tension or stress reversal. If the gaps are sufficiently wide, there may be sufficient "web gap" (constraint-relief gap) distance to allow the web to yield prior to fracture. However, if the gaps are narrow, then the combination of the transverse and longitudinal web stiffeners act to prevent local through-thickness yielding of the web. Thus, this type of detailing could be found to be susceptible to CIF. This type of detailing may exist in older bridges.

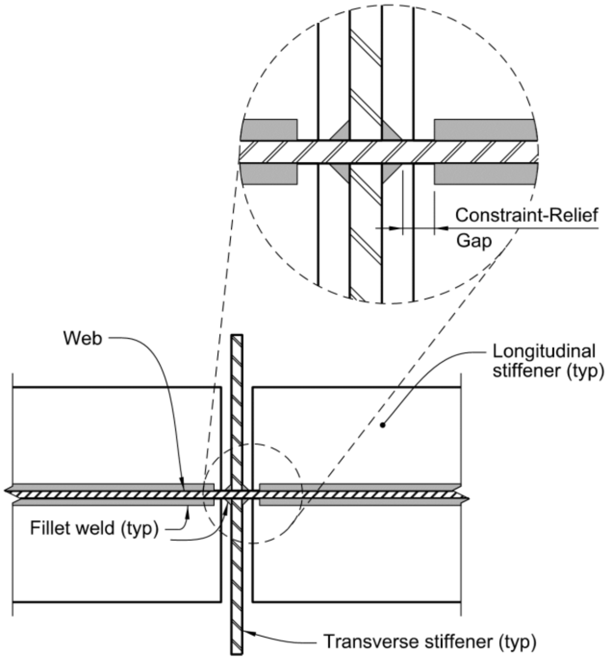
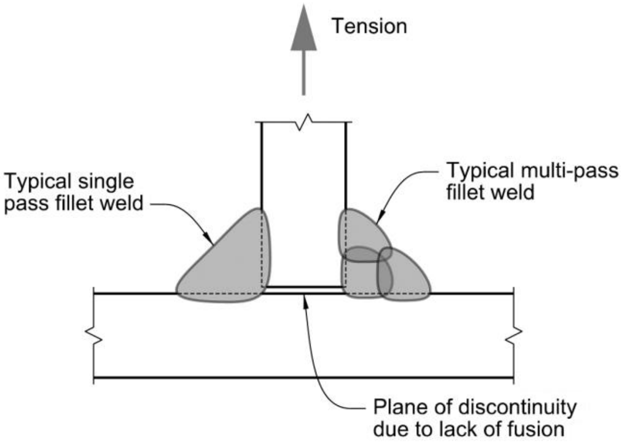


Figure 12. Plan view of girder web with attached transverse and longitudinal stiffeners.

Other examples of a planar discontinuity are less obvious. For example, the naturally occurring plane of unfused steel between back-to-back fillet welds, or in a partial joint penetration (PJP) weld, in a T-joint or a corner joint would represent a plane of discontinuity. See Figure 13 and Figure 14. These are not welding defects or imperfections. The welds shown in these figures meet applicable design and specification criteria, but by design, they are not intended to be full-penetration welds and so they naturally have some discontinuity. If the plane of this discontinuity is oriented perpendicular, or nearly perpendicular, to the primary flow of tension in the connection, that tension acts to try to open the discontinuity further, with stress concentrations at the ends of the discontinuity. Since the ends of discontinuity feature a narrow or sharp, "crack-like," geometry, they can serve as crack initiators.



Source: FHWA

Figure 13. Fillet welded T-joint subjected to tension.

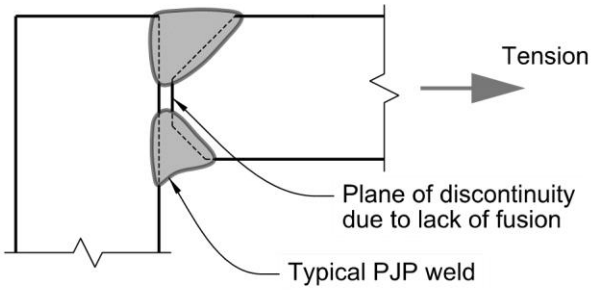


Figure 14. Partial joint penetration (PJP) corner joint subjected to tension.

Generally, elevated susceptibility to CIF is associated with the presence of all three conditions. An elevated susceptibility to CIF is possible when only two of the conditions exist, but these cases are relatively uncommon in most typical steel bridge structures. Consider the case of a highly constrained box weldment, such as that shown in Figure 15. Shown in the upper left portion of the figure is a four-sided box member with an interior plate at mid-depth. The four side plates are welded to each other with CJP welds and the interior plate is also welded to the four side plates with CJP welds. No constraint-relief gaps or other interruptions of the connections are provided. Such a detail would be subject to high residual stresses, resulting from the heating and cooling associated with the CJP welds, and would also be subject to a high level of constraint. Such a detail would be subject to an elevated susceptibility to CIF even if no externally applied tensile loading was present. In fact, a weldment such as this could potentially crack or fully fracture during fabrication. This is an extreme case; typically constraint-relief gaps (the “cut out” details shown in the upper right and lower portions of Figure 15) are provided, both to help relieve constraint and also to facilitate weld quality.

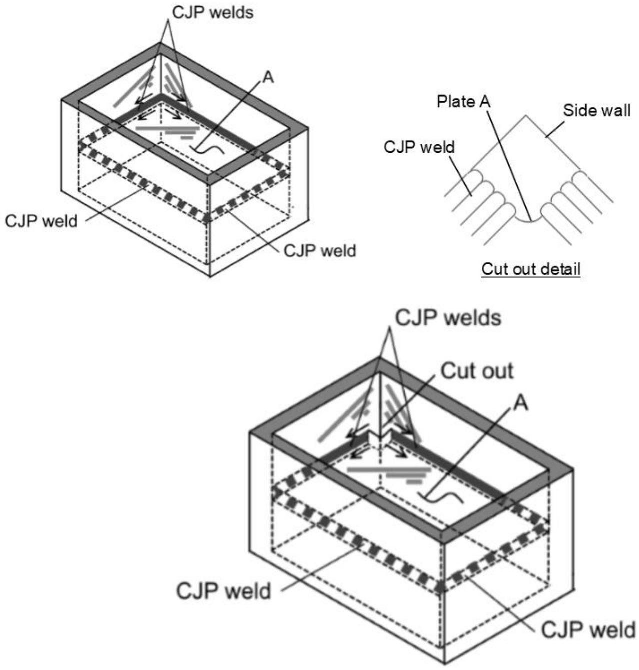


Figure 15. Highly constrained box weldment (Medlock et al., 2019).

It is likewise easy to imagine other scenarios where it may appear that only two of the three conditions exist, but the detail might still be subject to an elevated susceptibility to CIF. However, in most situations found in normal design practice, elevated susceptibility to CIF is associated with the presence of all three conditions.

With this understanding of the three conditions in mind, virtually any structural steel detail can be easily evaluated for susceptibility to CIF. A summary is provided below. Later in this report, the CIF evaluation procedure is summarized using a "scorecard" format. Numerical scoring values can be used to assign relative weights to conditions that can contribute to CIF. These weights are subjective; the scoring values used by the authors are presented below.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal. For the purposes of completing the "CIF Evaluation Scorecard," the following scoring values could be used:
>
> - **Cases where the area of interest is subjected to a net applied tensile stress or stress reversal: Score = 1.0**
> - **Cases where the area of interest is subjected to a net applied compressive stress under any and all conditions: Score = 0.0**
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** Details that feature the intersection of multiple welded steel elements, generally in a roughly orthogonal configuration, may be indicative of this condition. For example, a detail featuring the intersection of a web plate, a vertical stiffener, and a longitudinal stiffener or other longitudinal attachment, may be subject to a high degree of constraint. Consider the potential for some part of the detailing to offer relief to the constraint, such as the presence of an appropriately detailed and sized constraint-relief gap in the

constraining element. For the purposes of completing the "CIF Evaluation Scorecard," the following scoring values could be used:

- **Details featuring a high degree of triaxial constraint** (e.g., details that feature the intersection of three or more welded steel elements, generally in a roughly orthogonal configuration): **Score = 1.0**
- **Details featuring a moderate degree of biaxial constraint** (e.g., details that feature the intersection of two welded steel elements, generally in a roughly orthogonal configuration): **Score = 0.5**
- **Details featuring a low degree of constrain**t (e.g., details that feature no intersecting welded steel elements): **Score = 0.0**

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. In some cases, a planar discontinuity with crack-like or notch-like geometry may be easily recognized, but other cases may involve a more thoughtful evaluation. For example, it may be easy to identify a constraint-relief gap of insufficient width. But more subtle conditions may exist, such as "hidden" planes of discontinuity associated with incomplete fusion in welded connections. Such conditions may be "intentional" (e.g., lack of joint penetration in a T-joint made with fillet welds or a partial joint penetration weld) or "unintentional" (e.g., incomplete fusion in a difficult-to-accomplish complete joint penetration weld). The orientation of the plane of discontinuity is also important; a plane of discontinuity parallel to the primary flow of tension stress is generally not a concern, but a plane of discontinuity approximately perpendicular to the primary flow of tension stress is potentially problematic.

In some cases, the discontinuity may clearly be narrow and/or sharp and may obviously represent a "crack-like" condition. In other cases, a more careful examination may be warranted to determine whether the discontinuity is narrow or sharp enough to be considered "crack-like" or wide enough, with blunt enough tips, to be considered a sufficient constraint-relief gap. The key word is "planar," which indicates the discontinuity generally takes the form of a plane, i.e., "a flat surface on which a straight line joining any two points on it would wholly lie." This implies the discontinuity exhibits more of a two-dimensional geometry, rather than a three-dimensional geometry where the discontinuity has noticeable "depth." A discontinuity that has more of a three-dimensional geometry, where all three dimensions are of noticeable size, might be a candidate for consideration as a constraint-relief gap rather than a planar discontinuity.

Furthermore, it is important to consider the orientation of the planar discontinuity; a planar discontinuity parallel to the flow of primary tension stress is generally not a concern, but a planar discontinuity approximately perpendicular to the flow of primary tension stress is generally problematic.

For the purposes of completing the "CIF Evaluation Scorecard," the following scoring values could be used

- **Details featuring a planar discontinuity approximately PERPENDICULAR to the primary flow of tensile stress: Score = 1.0**
- **Details featuring a planar discontinuity approximately PARALLEL to the primary flow of tensile stress: Score = 0.0**
- **Details NOT featuring a planar discontinuity: Score = 0.0**

The scores for each of the three conditions could then be added to determine the total score for the evaluation. The following criteria could then be used to evaluate the total score.

For evaluation of new designs:

- **Details with a total score of 2.5 or higher: The detail has a HIGH level of susceptibility to CIF.** Actions that can be taken to redesign or reconfigure the detail to reduce the susceptibility to CIF typically include revising the detail so that an interrupted longitudinal element is made continuous, or reconfiguring the design to reduce the level of constraint.
- **Details with a total score of 2.0 or lower: The detail has a LOW level of susceptibility to CIF.** Redesign or reconfiguration of the detail is not indicated.

For evaluation of existing structures:

- **Details with a total score of 3.0: The detail has a HIGH level of susceptibility to CIF.** Actions that can be taken to retrofit the detail to reduce the level of susceptibility to CIF can be found in Connor and Lloyd (2017).
- **Details with a total score of 2.5: The detail MAY have a HIGH level of susceptibility to CIF.** Further evaluation of the structure could be undertaken to inform the decision about whether to implement some type of retrofit to reduce the level of susceptibility to CIF. Alternately, a conservative decision could be made, without further evaluation, to implement some type of retrofit to reduce the level of susceptibility to CIF.
- **Details with a total score of 2.0 or lower: The detail has a LOW level of susceptibility to CIF.** Retrofit of the structure is not indicated.

A lower threshold for new designs reflects that the redesign or reconfiguration of a detail in a new design is generally very easy to undertake without incurring increased cost or complexity.

Different criteria may be used for the evaluation of existing structures because retrofits can be costly and/or complicated and may have consequences beyond just structural considerations (e.g., impacts on the traveling public). The “further evaluation” actions in the case of an existing structure with a total score of 2.5 could include items such as more detailed inspections of the structure (perhaps to clarify the presence of crack-like or notch-like planes of discontinuity), refined analysis to more thoroughly understand the stresses in the element of interest, testing to measure the magnitude of residual stresses, etc. In addition, consideration can be given to the potential consequences of CIF if it were to occur. For example, the consequence of CIF in a non-redundant, two-girder, simple-span bridge carrying high volumes of traffic may be more severe than the consequence of CIF in a highly redundant, multi-girder, multiple-span continuous bridge carrying a very low volume of traffic.

To illustrate the CIF evaluation procedure, consider a detail similar to that shown previously in Figure 12. For illustration purposes, this example considers a single transverse web stiffener and a single longitudinal web stiffener, on the same side of the web. It should be emphasized that this type of detailing could be found to be susceptible to CIF as previously explained, and is only shown here for illustrative purposes. Figure 16 shows this scenario and includes a representation of the flow of an assumed longitudinal tension stress from the longitudinal stiffener into the girder web at the end of the longitudinal stiffener.

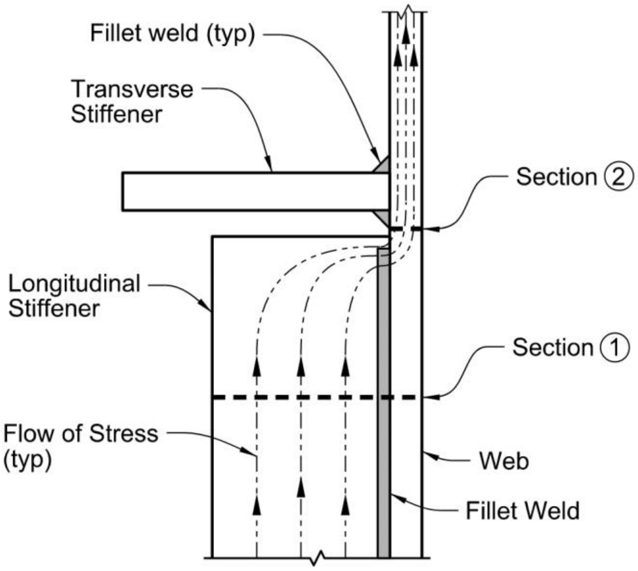


Figure 16. Flow of stress at the end of a longitudinal web stiffener.

At “Section 1,” at some distance away from the end of the longitudinal stiffener, the flow of stress is relatively uniformly distributed through the full cross-section of the longitudinal stiffener (and the web as well). The stress is tensile, and it can be assumed that there are tensile residual stresses present as well, so that overall it can be assumed that Condition 1, sufficiently high net tensile stress, including consideration of residual stresses, exists. Thus, for this example, the item “Tensile/Residual Stress” would be receive a score of 1.0 (high).

At “Section 1,” the presence of the longitudinal stiffener restricts through-thickness yielding of the web. In this instance, the presence of a longitudinal stiffener, but no other constraining elements, represents a case of biaxial constraint. Thus, for this example, the item “Degree of Constraint” would be receive a score of 0.5 (biaxial).

However, at “Section 1,” there is no discontinuity that interrupts the flow of stress. Recall the statement above: “the flow of stress is relatively uniformly distributed through the full cross-section of the longitudinal stiffener (and the web as well).” Therefore, Condition 3, a planar discontinuity approximately perpendicular to the primary flow of tensile stress, does not exist. Thus, for this example, the item “Planar Discontinuity” would be receive a score of 0.0 (not present). Lacking this third condition, it is reasonable to assume that, under normal circumstances, there is not an elevated susceptibility to CIF at “Section 1.”

The total score for this detail would then be the sum of the individual item scores of 1.0, 0.5 and 0.0, which totals to 1.5, and this detail would be characterized as having a low susceptibility to CIF.

A summary is provided in Table 1:

Table 1. CIF evaluation scorecard for "Section 1" in Figure 16.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial)
3. Planar Discontinuity	0.0 (not present)
TOTAL	**1.5 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category B detail per AASHTO BDS Table 6.6.1.2.3-1, Description 3.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

Next, at "Section 2," at the end of the longitudinal stiffener, the flow of stress from the longitudinal stiffener has transitioned into the web. The stress is tensile, and it can be assumed that there are tensile residual stresses present as well, so that overall it can be assumed that Condition 1, sufficiently high net tensile stress, including consideration of residual stresses, exists. Thus, for this example, the item "Tensile/Residual Stress" would be receive a score of 1.0 (high).

At "Section 2," the presence of the longitudinal stiffener and the transverse stiffener restrict through-thickness yielding of the web. In this instance, the presence of both a longitudinal stiffener and an orthogonally oriented transverse web stiffener represents a case of triaxial constraint. As a basic premise for this example, assume that the gap between the ends of the longitudinal stiffener-to-web welds and the toe of the transverse stiffener-to-web weld (the constraint-relief gap) is very small. Without a sufficiently sized constraint-relief gap to allow for through-thickness yielding of the web, it can be assumed that Condition 2, a high degree of constraint, preventing local yielding, exists. Thus, for this example, the item "Degree of Constraint" would be receive a score of 1.0 (triaxial).

Importantly, at "Section 2," there is a discontinuity that interrupts the flow of stress. The longitudinal stiffener has ended, and the stress formerly carried by that stiffener now suddenly redistributes into the web. A long, gradual transition of the longitudinal stiffener width is not provided, nor is a transition radius provided. The stiffener ends; its width changes from full width to zero width. A severe stress concentration can be expected at this location. Considering this, it can be seen that Condition 3, a planar discontinuity approximately perpendicular to the primary flow of tensile stress, exists. Thus, for this example, the item "Planar Discontinuity" would be receive a score of 1.0 (perpendicular).

The total score for this detail would then be the sum of the individual item scores of 1.0, 1.0, and 1.0. Therefore, the total score would be 3.0 and this detail would be characterized as having a high susceptibility to CIF.

A summary is provided in Table 2:

Table 2. CIF evaluation scorecard for "Section 2" in Figure 16.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	1.0 (triaxial)
3. Planar Discontinuity	1.0 (perpendicular)
TOTAL	**3.0 (high susceptibility to CIF)**

From a fatigue standpoint, the performance of this detail has been shown by Pass et al. (1983) and Platten (1980) to be worse than that of an E' detail per AASHTO BDS Table 6.6.1.2.3-1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

Next, as an academic exercise, consider a modified version of this detail, where the longitudinal stiffener is attached to the transverse stiffener with a CJP weld. Assume the CJP weld is perfectly fabricated and completely free from any discontinuities or other imperfections and has 100 percent fusion. See Figure 17.

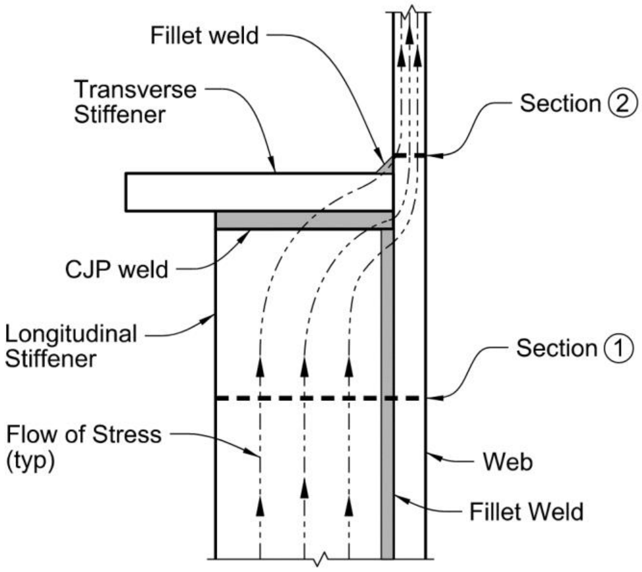


Figure 17. Flow of stress at the end of a longitudinal web stiffener, CJP welded to a transverse stiffener.

At “Section 1” in Figure 17, the conditions are nearly identical to the conditions at “Critical Section 1” in Figure 16. An evaluation of susceptibility to CIF at “Critical Section 1” in Figure 17 may produce the same conclusions; there is low susceptibility to CIF at “Section 1” in Figure 16.

However, at “Section 2” in Figure 17, the conditions are different from those at “Section 2” in Figure 16. There is still tension stress at “Section 2” in Figure 17, so Condition 2, sufficiently high net tensile stress, including consideration of residual stresses, exists. Thus, for this example, the item “Tensile/Residual Stress” would receive a score of 1.0 (high).

“Section 2” in Figure 17 is located just past the transverse stiffener. At this location, a discontinuity interrupts the flow of stress. The longitudinal stiffener is attached to the transverse stiffener, which acts as a de-facto extension of the longitudinal stiffener, but this combined element has ended, and the stress formerly carried by that stiffener redistributes into the web. A long, gradual transition of the longitudinal stiffener width is not provided, nor is a transition radius provided. The stiffener ends; its width changes from full width to zero width. A severe stress concentration can be expected at this location. Considering this, Condition 3, a planar discontinuity approximately perpendicular to the primary flow of tensile stress, exists. Thus, for this example, the item “Planar Discontinuity” would receive a score of 1.0 (perpendicular).

However, at “Section 2” in Figure 17, the degree of constraint is different from that at “Section 2” in Figure 16. Without the longitudinal stiffener, the web is free to experience through-thickness yielding past the transverse stiffener. As a result, Condition 2, a high degree of constraint preventing local yielding, is not present. Thus, for this example, the item “Degree of Constraint” would receive a score of 0.0 (low).

Lacking the condition of constraint, it is reasonable to assume that, under normal circumstances, there is not an elevated susceptibility to CIF at “Critical Section 2” in Figure 17. The total score for this detail would then be the sum of the individual item scores of 1.0, 0.0, and 1.0. Therefore, the total score is 2.0 and this detail would be characterized as having a low susceptibility to CIF.

Note that although there is a low susceptibility to CIF at both “Section 2” and “Section 1” in Figure 17, the detailing represented in this figure would still exhibit very poor fatigue performance, comparable to or worse than an AASHTO Category E or E' detail depending on the size of the longitudinal stiffener (see Pass et al., 1983 and Patten, 1980). Remember, there is still a very severe stress concentration at “Critical Section 1” and there is a significant amount of tensile stress in the long attachment represented by the longitudinal stiffener, which migrates suddenly from that stiffener into the web at the termination of the stiffener-to-web weld.

A summary of the evaluation for “Section 2” in Figure 17 is provided in a scorecard format in Table 3:

Table 3. CIF evaluation scorecard for “Section 2” in Figure 17.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.0 (low)
3. Planar Discontinuity	1.0 (perpendicular)
TOTAL	**2.0 (low susceptibility to CIF)**

From a fatigue standpoint, the performance of this detail would be expected to be comparable to, or worse than, that of a category E or E' detail (Pass et al., 1980, and Patten, 1983).

4.2 FATIGUE VERSUS CONSTRAINT-INDUCED FRACTURE (CIF)

Some details may not be subject to an elevated susceptibility to CIF, but may exhibit poor fatigue performance. The difference between details that may exhibit poor fatigue performance and those subject to an elevated susceptibility to CIF is noteworthy. CIF represents a sudden, brittle failure mode, providing virtually no warning prior to the fracture event. Fatigue cracking, on the other hand, typically occurs over a longer period, allowing some opportunity for identification of the cracks during periodic in-service bridge inspections.

Neither increased susceptibility to CIF nor poor fatigue performance is a desirable characteristic in a steel bridge detail, but it is important to differentiate the two conditions as they exhibit different performance and may warrant different mitigation approaches. In all cases, both fatigue performance and susceptibility to CIF should be evaluated. Even a detail with low susceptibility to CIF may still exhibit poor fatigue performance, or vice versa.

In the example evaluations of common details (Section 4.3), the fatigue category of each detail, when defined in the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)), is listed to help illustrate these concepts.

4.3 CONCERNS ABOUT DETAILS WITH INTERSECTING WELDS

Proper understanding of CIF provides bridge designers the ability to assess if details featuring intersecting welds are potentially problematic. Intersecting welds are not, in and of themselves, necessarily problematic. Instead, details with high degrees of constraint and crack-like or notch-like planes of discontinuity approximately perpendicular to the primary flow of tensile stress may exhibit elevated susceptibility to CIF.

Examples of commonly used steel bridge details featuring intersecting welds are evaluated in Chapter 5, where it is shown that these details are not subject to an elevated susceptibility to CIF.

This is not to say that details involving the intersection of welds are always free of any concerns. There are some caveats, primarily associated with the potential for the introduction of weld imperfections or discontinuities in highly complex weld details or in weld details that are difficult to fabricate. Such weld imperfections or discontinuities may represent a point of crack initiation or a failure plane, possibly leading to the following:

- greater chance of fatigue cracking in details that are otherwise fatigue-prone; or
- greater susceptibility to CIF in details that otherwise also feature a high degree of triaxial constraint.

As discussed in this report, details with welds that happen to intersect are not necessarily problematic. Details can be evaluated regarding the potential for a high degree of triaxial constraint, and/or for crack-like or notch-like planes of discontinuity approximately perpendicular to the primary flow of tensile stress, to evaluate their level of susceptibility to CIF.

4.4 CONDITIONS OR DETAILS WHERE INTERSECTING WELDS ARE APPROPRIATE

There are many situations where the use of details featuring intersecting welds may be advantageous. For example, many routine details (such as details involving the intersection of flange-to-web fillet welds with flange shop splices accomplished using CJP groove welds in butt joints) offer advantages in terms of efficient structural performance, ease of fabrication, or practicality. In other cases, such as sealing faying surfaces, the intersection of welds is unavoidable, but provides for beneficial corrosion protection. In addition, there may be other, less common or less obvious situations where the use of details with intersecting welds may be beneficial.

CHAPTER 5 - EXAMPLE EVALUATIONS OF COMMON INTERSECTING WELD DETAILS

There are many commonly used steel bridge details that feature intersecting or nearly intersecting welds. Some of the more prevalent are discussed in this section. Each detail is subjected to the evaluation procedure described in Section 4.1, and commentary is provided regarding the detail's potential advantages or disadvantages.

5.1 INTERSECTION OF FLANGE-TO-WEB WELDS WITH WELDED FLANGE SHOP SPLICES

One of the most common bridge details featuring intersecting welds is the intersection of flange-to-web fillet welds with flange shop splices accomplished using CJP groove welds in butt joints. This situation is unavoidable in many bridge designs. The flange shop splice is generally accomplished prior to attaching the flange to the web. While there are clearly intersecting welds in this detail, both a qualitative evaluation and a long history of good performance support that this detail is not subject to an elevated susceptibility to CIF. See Figure 18 and Figure 19.

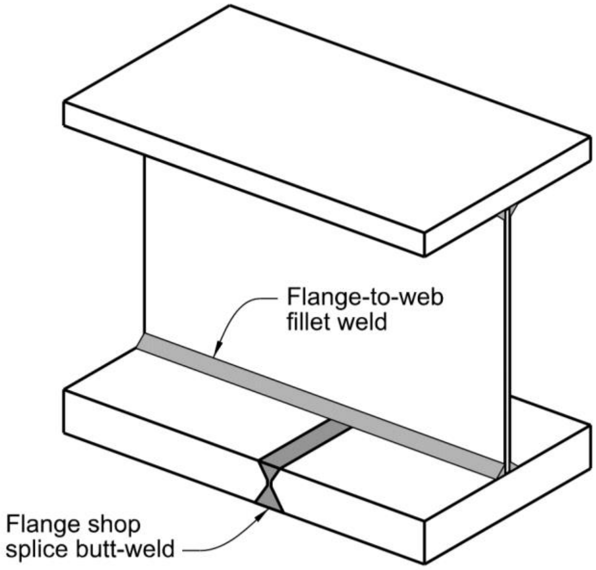


Figure 18. Intersection of flange-to-web fillet welds with a CJP groove weld in a butt joint used to accomplish a flange shop splice.

Figure 19. Steel plate girder with flange-to-web welds intersecting CJP groove welds in butt joints used to accomplish flange and web shop splices.

To demonstrate that this detail is not subject to an elevated susceptibility to CIF, evaluate the detail using the procedure described in Section 4.1.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** At their juncture, the flange prevents local through-thickness yielding of the web to some degree, although the constraint is biaxial, not triaxial. Thus, this detail would receive a score of 0.5 in this category.
>
> ***Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress.*** First, look for obvious, immediately visible examples of crack-like or notch-like geometry, such as discrete cut-outs or notches – there are no such features in this detail. Next, consider the welds. The CJP groove welds in butt joints used to fabricate shop splices of flange plates are easily accomplished. These types of shop splice welds are typically performed in the flange and web plates prior to their being welded together into a full plate girder, are accomplished under controlled conditions in a fabrication shop, and are subjected to thorough inspection and testing, which provides a high level of assurance of quality. Consequently, it is reasonable to assume there are no planar discontinuities in the CJP welds used in the butt joints. On the other hand, there are planar discontinuities in the fillet-welded T-joints connecting the flanges to the web (due to intentional lack of joint penetration between the fillet welds), but they are oriented parallel to the primary flow of tensile stress in the flanges and the web. Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 4:

Table 4. CIF evaluation scorecard for the intersection of flange-to-web fillet welds with a CJP groove weld in a butt joint used to accomplish a flange shop splice.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial)
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category B or B' detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1 and 5.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

5.2 INTERSECTION OF FLANGE-TO-WEB WELDS WITH WELDED WEB SHOP SPLICES

A similar, related detail involves the intersection of flange-to-web fillet welds with web shop splices accomplished using CJP groove welds in butt joints. This case of intersecting welds is also, for all practical purposes, unavoidable in many bridge designs. The web shop splice is generally accomplished prior to attaching the web to the flange. See Figure 19 and Figure 20.

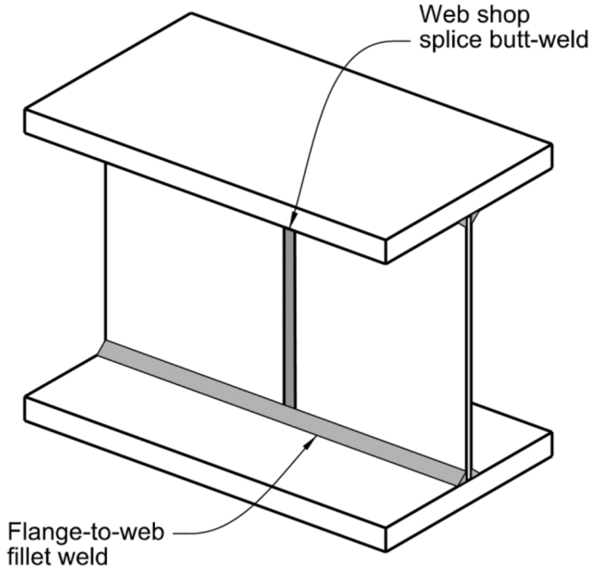


Figure 20. Intersection of flange-to-web fillet welds with a CJP groove weld in a butt joint used to accomplish a web shop splice.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF. The evaluation is very similar to that for the case of flange-to-web welds intersecting a flange shop splice (see Section 5.1).

Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses. As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.

Condition 2: A high degree of constraint, preventing local yielding. At their juncture, the flange prevents local through-thickness yielding of the web to some degree, although the constraint is biaxial, not triaxial. Thus, this detail would receive a score of 0.5 in this category.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. This condition is not present in this type of detail. There is no obvious crack-like or notch-like geometry (no discrete cut-outs or notches). There is also very little chance of a “hidden” plane of discontinuity in the welds. The CJP groove welds in butt joints used to fabricate shop splices of web plates are easily accomplished, since these types of shop splices are typically performed in the flange and web plates prior to their being welded together into a full plate girder. These welds are also subjected to thorough inspection and testing, providing a high level of assurance of quality. There is a possibility of a plane of discontinuity in the T-joint of the flange and the web (due to incomplete fusion between the fillet welds), but such a plane of discontinuity would be oriented parallel to the flow of primary tension stress in the flanges and the web. Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 5:

Table 5. CIF evaluation scorecard for the intersection of flange-to-web fillet welds with a CJP groove weld in a butt joint used to accomplish a web shop splice.

ITEM	**SCORE**
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (moderate)
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category B or B' detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1 and 5.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

5.3 INTERSECTION OF TRANSVERSE STIFFENER-TO-WEB WELDS WITH WELDED WEB LONGITUDINAL SHOP SPLICES

A similar, related detail involves the intersection of transverse (vertical) stiffener-to-web fillet welds with a web longitudinal shop splice accomplished using a CJP groove weld in a butt joint. This detail is perhaps less common since longitudinal shop splices of a web generally occur only in girders with very deep webs, but in such bridges, this detail would be difficult to avoid. See Figure 21.

A related evaluation of CIF at the intersection of the transverse stiffeners, the girder web, and the girder flange is provided in Section 6.1.

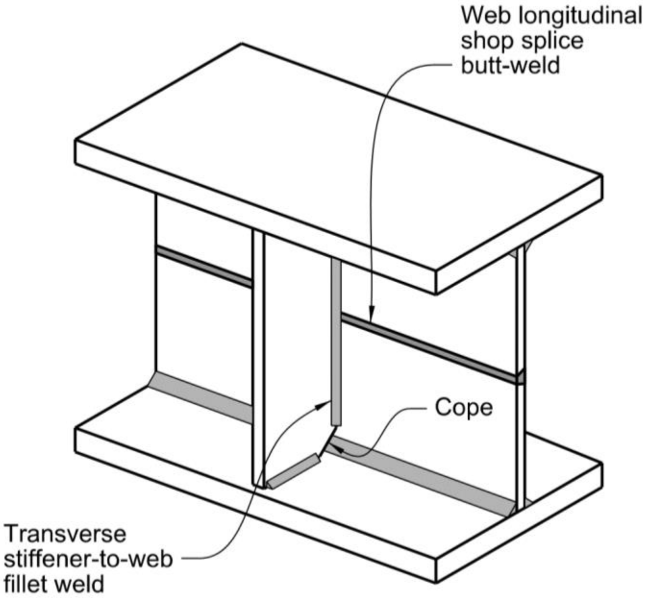


Figure 21. Intersection of transverse stiffener-to-web fillet welds with a CJP groove weld in a butt joint used to accomplish a web longitudinal shop splice.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** At their juncture, the transverse stiffener prevents local through-thickness yielding of the web to some degree, but the constraint is biaxial, not triaxial, and more importantly the constraint only affects a short distance in the direction of the primary flow of tensile stress. The web could easily yield on either side of the stiffener. Thus, this detail would receive a score of 0.0 in this category.
>
> ***Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress.*** This condition is not present in this type of detail. There is no obvious crack-like or notch-like geometry (no discrete cut-outs or notches). There is also very little chance of a “hidden” plane of discontinuity in the welds. The CJP groove welds in butt joints used to fabricate shop splices of web plates are easily accomplished, since these types of shop splices are typically performed in the flange and web plates prior to their being welded together into a full plate girder. These welds are also subjected to thorough inspection and testing, providing a high level of assurance of quality. There is a possibility of a plane of discontinuity in the T-joint of the transverse web stiffener and the web plate (due to incomplete fusion between the fillet welds), but such a plane of discontinuity would be oriented parallel to the flow of primary tension stress in the web. Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 6:

Table 6. CIF evaluation scorecard for the intersection of transverse stiffener-to-web fillet welds with a CJP groove weld in a butt joint used to accomplish a web longitudinal shop splice.

ITEM	**SCORE**
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.0 (low)
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.0 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category C' detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1, 4.1, and 5.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

CHAPTER 6 - EXAMPLE EVALUATIONS OF COMMON DETAILS WITH VERTICALLY ORIENTED STIFFENERS

Many commonly used steel bridge details feature vertically oriented stiffeners (such as transverse web stiffeners, transverse connection plates, or bearing stiffeners). Some of the more prevalent are discussed in this section. Each detail is evaluated under the procedure described in Section 4.1, and commentary is provided regarding the detail's potential advantages or disadvantages.

6.1 INTERSECTION OF A TRANSVERSE WEB STIFFENER WITH A GIRDER WEB AND A GIRDER FLANGE

A number of common steel girder bridge details feature the intersection of three welded steel plates configured in a roughly orthogonal arrangement, such as details involving transverse web stiffeners, transverse connection plates, or bearing stiffeners.

Transverse webs stiffeners are provided to increase the shear resistance of the web. These stiffeners are typically welded to the web and to at least one if not both flanges, usually using fillet welds. At locations where the stiffener is welded to both the web and the flange, there exists an instance of the intersection of three orthogonal structural elements (the web, the flange, and the transverse stiffener). Generally, the inside corners of these stiffeners (the corners of the stiffener plates near the intersection of the girder flange and girder web) are coped to clear the continuous girder flange-to-web fillet weld. See Figure 22.

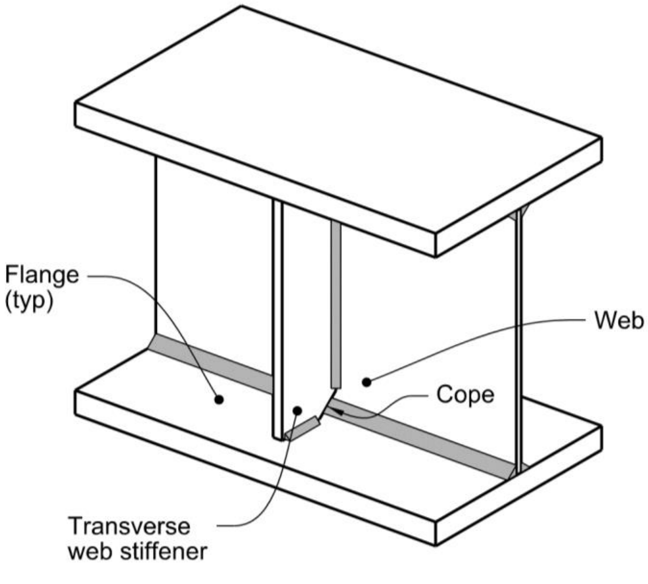


Figure 22. Intersection of a transverse web stiffener with a girder web and a girder flange.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** At their juncture, the flange and the transverse web stiffeners prevent local through-thickness yielding of the web. However, a

constraint-relief gap is provided by means of the copes of the stiffener; this provides relief of what might otherwise have been triaxial constraint of the web at the location of high tensile stresses in the web and the flange. So at any given position, the constraint would be biaxial. Thus, this detail would receive a score of 0.5 in this category.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. There is not a planar discontinuity approximately perpendicular to the primary flow of stress in this detail. The planes of discontinuity that might exist if there is incomplete fusion between the fillet welds connecting the transverse web stiffener to the girder flange or the girder web are parallel to the primary flow of tensile stress. Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 7:

Table 7. CIF evaluation scorecard for the intersection of a transverse web stiffener with a girder web and a girder flange.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial)
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category C' detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1 and 4.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

6.2 INTERSECTION OF BEARING STIFFENERS WITH A GIRDER WEB AND A GIRDER FLANGE

Bearing stiffeners represent a very similar detail to transverse web stiffeners. Again, these stiffeners are typically welded to the web using fillet welds and to at least one if not both flanges, preferably using fillet welds. At locations where the stiffeners are welded to both the web and the flange, there exists an instance of the intersection of three orthogonal structural elements (the web, the flange, and the bearing stiffeners). Generally, the inside corners of these stiffeners (the corners of the stiffener plates near the intersection of the girder flange and girder web) are coped to clear the continuous girder flange-to-web fillet weld. However, bearing stiffeners are often noticeably thicker than transverse web stiffeners, and often also function as connection plates for cross-frames or diaphragms. See Figure 23 (the bearing stiffener on the other side of the web is not visible in this view).

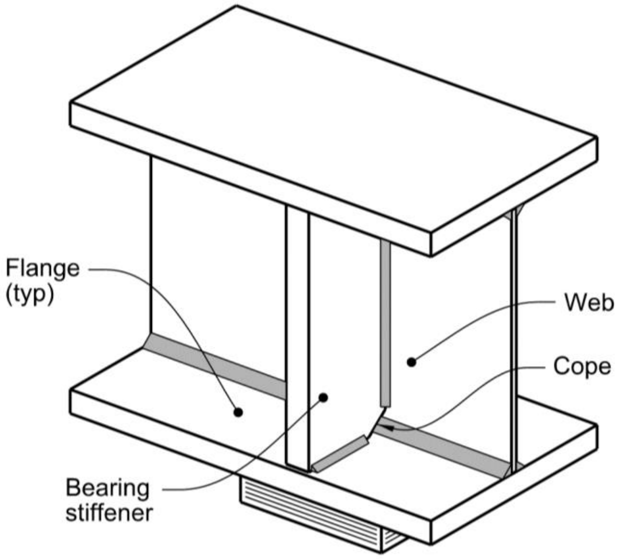


Figure 23. Intersection of bearing stiffeners with the girder web and a girder flange.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** At their juncture, the flange and the bearing stiffeners prevent local through-thickness yielding of the web. Bearing stiffeners are often noticeably thicker than transverse web stiffeners, providing more constraint. However, a constraint-relief gap is provided by means of the copes of the stiffeners; this provides relief of what might otherwise have been triaxial constraint of the web at the location of high tensile stresses in the web and the flange. So at any given position, the constraint would be biaxial. Thus, this detail would receive a score of 0.5 in this category.
>
> ***Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress.*** There is not a planar discontinuity approximately perpendicular to the primary flow of stress in this detail. The planes of discontinuity that might exist if there is incomplete fusion between the fillet welds connecting the bearing stiffeners to the girder flange or the girder web are parallel to the primary flow of tensile stress. Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in a scorecard format in Table 8:

Table 8. CIF evaluation scorecard for intersection of bearing stiffeners with a girder web and a girder flange.

ITEM	**SCORE**
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial)
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category C' detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1 and 4.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

6.3 INTERSECTION OF A TRANSVERSE CONNECTION PLATE WITH A GIRDER WEB AND A GIRDER FLANGE (WELDED TO BOTH FLANGES)

The third of this group of similar details involves transverse connection plates. A transverse connection plate is a transverse web stiffener or bearing stiffener that also functions to connect a cross-frame or diaphragm to the girder. Transverse connection plates in new designs are designed to be welded to the web and to both flanges per Article 6.10.11.1.1 of the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)). Typically, fillet welds are used for these attachments. Generally, the inside corners of these stiffeners (the corners of the stiffener plates near the intersection of the girder flange and girder web) are coped to clear the girder’s flange-to-web fillet weld. See Figure 24.

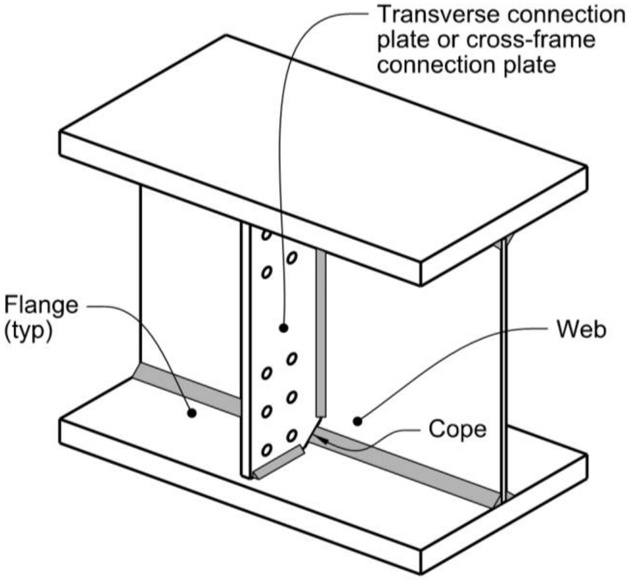


Figure 24. Intersection of a transverse connection plate with a girder web and a girder flange (welded to both flanges).

The attachment of a cross-frame to the transverse connection plate can potentially introduce out-of-plane loading on the web. However, the relative stiffness of the transverse connection plate’s attachment to the flanges suggests that most of that loading would be distributed to the flanges and not cause significant out-of-plane loading of the web. Article 6.10.11.1.1 of the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)) includes provisions for attachment of transverse connection plates to the girder flanges and webs which minimize the chances of distortion-induced fatigue in the web.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.

Condition 2: A high degree of constraint, preventing local yielding. At their juncture, the flange and the transverse connection plates prevent local through-thickness yielding of the web. Furthermore, the cross-frame members attached to the transverse connection plate, if loaded in tension, could exacerbate the constraint of the web, although the relative stiffness of the transverse connection plate's attachment to the flanges suggests that a significant portion of that loading would be distributed to the flanges without causing significant out-of-plane loading of the web.A constraint-relief gap is provided by means of the copes of the stiffener; this provides relief of what might otherwise have been triaxial constraint of the web at the location of high tensile stresses in the web and the flange. So at any given position, the constraint would be biaxial. Thus, this detail would receive a score of 0.5 in this category. This specific example situation assumes the thickness of the transverse connection plate is in the typical range of transverse connection plate thicknesses (i.e., in the range of approximately 5/8 inch to ¾ inch thick). The example shown in Section 6.4 features a bearing stiffener with unique connection details demonstrates that if the transverse connection plate is also functioning as a bearing stiffener and is much thicker, the degree of constraint may be greater.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. In this detail, there are no planar discontinuities approximately perpendicular to the primary flow of stress. Planar discontinuities might exist if there is incomplete fusion in the fillet welds connecting the transverse connection plate to the girder flange or the girder web, but those planes would be parallel to the primary flow of tensile stress. Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 9:

Table 9. CIF evaluation scorecard for the intersection of a transverse connection plate with a girder web and a girder flange (welded to both flanges).

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial)
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category C' detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1 and 4.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

6.4 INTERSECTION OF A BEARING STIFFENER (ALSO FUNCTIONING AS A TRANSVERSE CONNECTION PLATE) WITH A GIRDER WEB AND A GIRDER FLANGE (WELDED TO THE COMPRESSION FLANGE ONLY)

This detail is essentially the same as the detail discussed in Section 6.2, except that in this case the transverse connection plate is welded only to the compression flange, and is not welded to the tension flange. This type of detailing is suspected of contributing to fractures in at least two existing bridges (Fisher et al., 2010, Hodgson et al., 2018). Transverse connection plates in new designs are intended to be welded to the web and both flanges per Article 6.10.11.1.1 of the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)), but in some older designs, a transverse connection plate that was also functioning as a bearing stiffener might not be welded to the tension flange (e.g., the top flange at an interior support of a multiple-span continuous bridge). See Figure 25, which also shows the cracking reported by Hodgson et al. (2018) at a similar detail that experienced an in-service fracture. The orientation of the cracks in this figure suggests the nature of the out-of-plane bending imposed in the web by the cross-frame members attached to the connection plate - the cracks are oriented horizontally, indicating a vertical flow of tensile stress in at least one face of the web.

This represents an unusual situation with a very complicated state of stress in the web. In addition to the web being subjected to tensile stress in the longitudinal direction due to major-axis bending of the girder, it might also be subjected to out-of-plane bending stresses induced by the forces in the cross-frame members connected to the bearing stiffener (which is also functioning as a transverse connection plate), since the stiffener is not welded to the tension flange. These out-of-plane bending stresses would be acting in a vertical direction, with the flow of tensile stress being vertical in one face of the web. This would orient the flow of tensile stress parallel to an "attachment" (i.e., the bearing stiffener), so that the "end" of the attachment (the end of the bearing stiffener not welded to the tension flange) would represent a planar discontinuity approximately perpendicular to the flow of the vertical tensile stress in that face of the web.

If the effective constraint-relief gap (i.e., the "web gap" between the flange-to-web weld and the ends of the stiffener-to-web welds) is narrow, there would be a high degree of triaxial constraint at this same location, resulting in an elevated susceptibility to CIF. In fact, there have been reported cases of CIF occurring in bearing stiffeners with this type of detailing (Hodgson et al., 2018, Fisher and Kaufmann 2010).

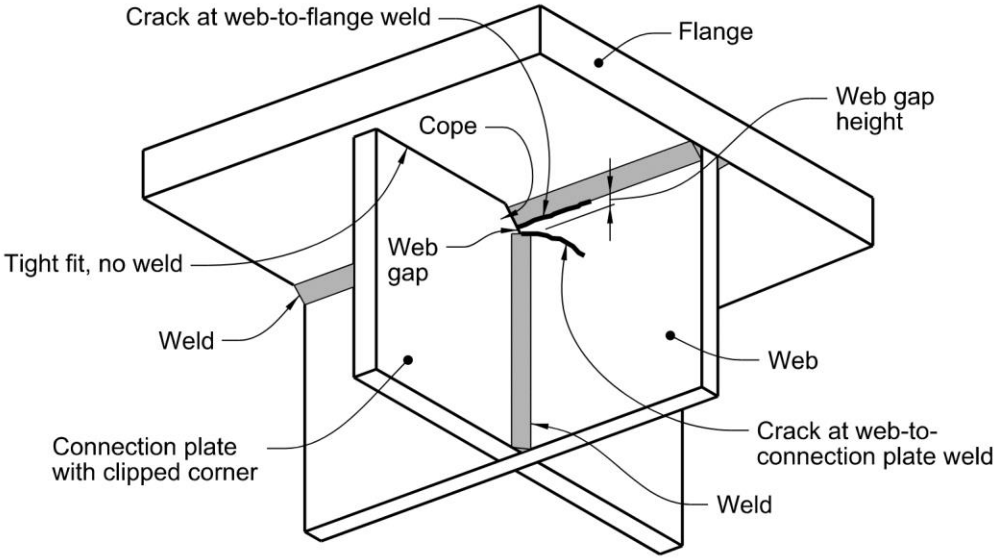


Figure 25. Intersection of a bearing stiffener also functioning as a transverse connection plate with a girder web and a girder flange (welded to the compression flange only).

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members

or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.

Condition 2: A high degree of constraint, preventing local yielding. At their juncture, the flange and the bearing stiffeners prevent local through-thickness yielding of the web. Bearing stiffeners are often much thicker than typical transverse web stiffeners or transverse connection plates, increasing the constraint of the web. Furthermore, in this example, there are cross-frame members attached to the bearing stiffeners, so they are also functioning as transverse connection plates. The cross-frame members, when loaded in tension, would impose a larger orthogonal stress on the web (exacerbating the constraint of the web). A constraint-relief gap is provided by means of the copes of the stiffener; if large enough, this constraint-relief gap could provide relief of what would otherwise be triaxial constraint of the web at the location of high tensile stresses in the web and the flange. However, a large gap here would also likely result in an elevated susceptibility to distortion-induced fatigue cracking. For the purposes of this evaluation, assume the gap is small and that thus the degree of constraint is high. Thus, this detail would receive a score of 1.0 in this category.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. The top termination of the attachment of the bearing stiffener/connection plate to the web represents a planar discontinuity approximately perpendicular to one of the primary flows of tensile stress - in this case, the out-of-plane bending stress induced in the web by the cross-frame member forces. Thus, this detail would receive a score of 1.0 for the planar discontinuities perpendicular to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 10:

Table 10. CIF evaluation scorecard for the intersection of a bearing stiffener / transverse connection plate with a girder web and a girder flange (welded to the compression flange only).

ITEM	**SCORE**
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	1.0 (triaxial)
3. Planar Discontinuity	1.0 (perpendicular)
TOTAL	**3.0 (high susceptibly to CIF)**

From a fatigue standpoint, there is no comparable detail in AASHTO BDS Table 6.6.1.2.3-1, (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

To reiterate earlier discussion, this type of detailing is suspected of contributing to fractures in at least two existing bridges (Fisher et al., 2010, Hodgson et al., 2018), **and this type of detailing should not be used**. The provisions of the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)) for stiffeners functioning as transverse connection plates require attaching to both flanges of the girder.

One way to reduce susceptibility to CIF for this type of detail would be attaching the transverse connection plate to both flanges of the girder.

6.5 INTERSECTION OF A COPED, SEAL-WELDED TRANSVERSE STIFFENER, BEARING STIFFENER, OR TRANSVERSE CONNECTION PLATE, WITH A GIRDER WEB AND A GIRDER FLANGE

Consider a modified version of the typical transverse web stiffener, bearing stiffener, or transverse connection plate (discussed in Sections 6.1, 6.2, and 6.3, respectively). Assume that a cope is provided in the corners of the stiffener to clear the continuous flange-to-web weld, similar to the previously described details. However, in this case, assume the fillet welds wrap around all the free edges of the stiffener as a corrosion protection measure. This type of detailing facilitates sealing the faying surfaces of the stiffener. See Figure 26, which shows a typical transverse connection plate; the welded connections would be similar for bearing stiffeners or a transverse web stiffener. See also Appendix E, which discusses welding mock-up trials of similar details and includes photos.

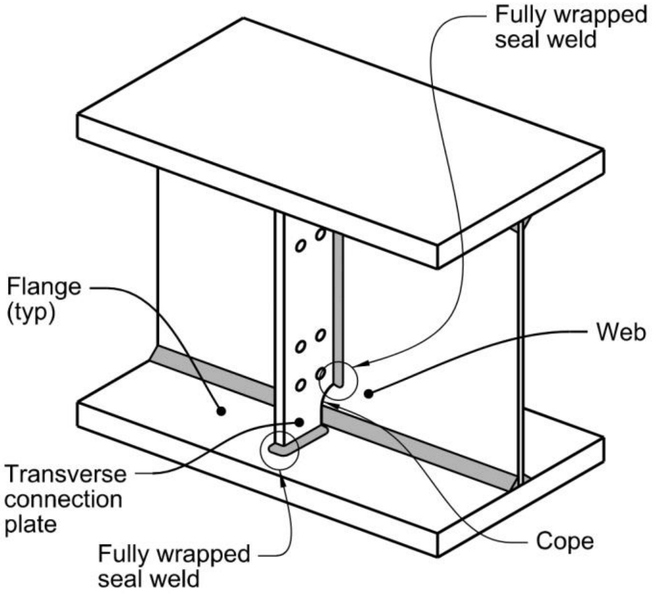


Figure 26. Intersection of a coped, seal-welded transverse connection plate with a girder web and a girder flange.

The attachment of a cross-frame to the transverse connection plate could potentially introduce out-of-plane loading on the web. However, the relative stiffness of the transverse connection plate's attachment to the flanges suggests that a significant portion of that loading would be distributed to the flanges without causing significant out-of-plane loading of the web.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** At their juncture, the flange and the transverse stiffener or connection plate prevent local through-thickness yielding of the web. If the stiffener also functions as a bearing stiffener, it would likely be thicker than a typical

transverse web stiffener, increasing the level of constraint. If the stiffener is also functioning as a transverse connection plate, the attached cross-frame members, if loaded in tension, could exacerbate the constraint of the web. However, since a cope is provided in the corner of the stiffener, there is an opportunity to introduce constraint-relief gaps. The size of the constraint-relief gaps would be measured between the toes of the flange-to-web welds and the welds that seal the faying surfaces of the stiffener; if these constraint-relief gaps are too small, they may not provide sufficient relief of the constraint, but if they are adequately sized, they may provide sufficient relief. The size of the stiffener corner copes could also potentially be too large; as explained in C6.10.11.1.1 of the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)), the maximum size of the cope is limited to avoid vertical buckling of the unsupported web. From a scoring standpoint, this detail would receive a score of 0.5 if the constraint-relief gaps are sized sufficiently, or 1.0 if the constraint-relief gaps are not large enough.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. There is not a planar discontinuity approximately perpendicular to the primary flow of stress in this detail. The planes of discontinuity that might exist if there is incomplete fusion between the fillet welds connecting the stiffener plate to the girder flange or the girder web are parallel to the primary flow of tensile stress. Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 11:

Table 11. CIF evaluation scorecard for the intersection of a coped, seal-welded transverse stiffener, bearing stiffener, or transverse connection plate with a girder web and a girder flange.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial) to 1.0 (triaxial) depending on the size of the constraint-relief gaps
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 to 2.0 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category C' detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1 and 4.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

6.6 INTERSECTION OF A CONTINUOUSLY SEAL-WELDED TRANSVERSE STIFFENER, BEARING STIFFENER, OR TRANSVERSE CONNECTION PLATE, WITH A GIRDER WEB AND A GIRDER FLANGE

Consider next a modified version of the typical transverse web stiffener, bearing stiffener, or transverse connection plate (discussed in Sections 6.1, 6.2, and 6.3, respectively). Rather than providing a cope in the corners of the stiffener to clear the flange-to-web weld, instead assume the fillet welds connecting the stiffener to the web and flanges are continuous. Assume the fillet welds wrap around the free edges of the stiffener and continue back into the corner where the stiffener, the web, and the flange intersect. This type of detailing facilitates sealing the faying surfaces of the stiffener as a corrosion protection measure. See Figure 27, which shows a typical transverse web stiffener; the welded connections would be similar for bearing stiffeners or a transverse connection plate. See also Appendix E, which discusses welding mock-up trials of similar details and includes photos.

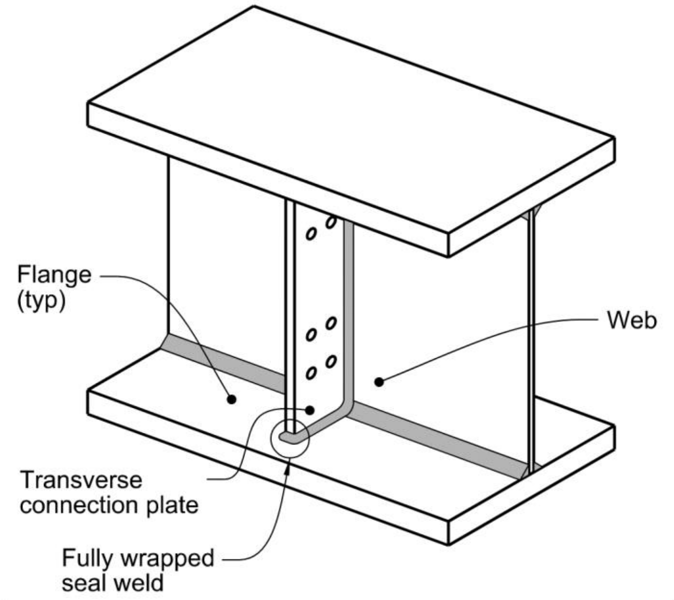


Figure 27. Intersection of a continuously seal-welded transverse connection plate with a girder web and a girder flange.

The attachment of a cross-frame to the transverse connection plate could potentially introduce out-of-plane loading on the web. However, the relative stiffness of the transverse connection plate's attachment to the flanges suggests that a significant portion of that loading would be distributed to the flanges without causing significant out-of-plane loading of the web.

This type of continuously welded stiffener/connection plate detail is not known to have been tested or used in steel bridges in the United States. As such, this detail does not yet have a documented record of good performance in bridges. However, this type of detailing has been widely used in the petroleum industry (API, 2014 and Bucknall, 2000) and in Japan (Verma, 2001) with no known reports of problems. Due to the lack of testing in steel bridge applications in the United States, further study of this detail is currently underway.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** At their juncture, the flange and the stiffener plates prevent local through-thickness yielding of the web. If the stiffener also functions as a bearing stiffener, the stiffener would likely be thicker than a typical transverse web stiffener, increasing the level of constraint. If the stiffener is also functioning as a transverse connection plate, the attached cross-frame members, if loaded in tension, could exacerbate the constraint of the web. Since the stiffener is continuously welded into the corner where the stiffener, the web, and the flange intersect, there is no constraint-relief gap, and thus no local relief of the constraint. At the juncture of the stiffener, the web, and the flange, a high degree of triaxial

constraint of the web would be expected. Thus, this detail would receive a score of 1.0 in this category.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. There is not a planar discontinuity approximately perpendicular to the primary flow of stress in this detail, assuming the stiffener has an appropriate controlled fit not only to the girder flanges and web, but also to the flange-to-web welds. The planes of discontinuity that might exist if there is incomplete fusion between the fillet welds connecting the stiffeners to the girder flange or the girder web are parallel to the primary flow of tensile stress. Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 12:

Table 12. CIF evaluation scorecard for the intersection of a continuously seal-welded transverse connection plate with a girder web and a girder flange.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	1.0 (triaxial)
3. Planar Discontinuity	0.0 (parallel) assuming the stiffener has an appropriate controlled fit not only to the girder flanges and web, but also to the flange-to-web welds
TOTAL	**2.0 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category C' detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1 and 4.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

Key for successful implementation of this type of detailing would be providing an appropriate controlled fit of the stiffener not only to the girder web and flange, but also to the flange-to-web welds. An excessively large gap in this region might result in the temptation to fill the gap with excess weld metal. Such practices could lead to increased opportunities to introduce welding discontinuities and imperfections that could manifest themselves as crack-like or notch-like planes of discontinuity approximately perpendicular to the primary flow of tensile stress, one of the three conditions associated with elevated susceptibility to CIF.

CHAPTER 7 - EXAMPLE EVALUATIONS OF COMMON DETAILS WITH LONGITUDINALLY ORIENTED STIFFENERS OR ATTACHMENTS

A number of commonly used steel bridge details feature longitudinally oriented stiffeners or attachments (such as longitudinal web stiffeners or lateral connection plates). Some of the more prevalent are discussed in this section. Each detail is subjected to the evaluation procedure described in Section 4.1, and commentary is provided regarding the detail's potential advantages or disadvantages.

7.1 INTERSECTION OF A LONGITUDINAL WEB STIFFENER WITH A WEB SHOP SPLICE

A common steel bridge detail involves the intersection of a longitudinal web stiffener (attached to the web with fillet welds) intersecting a web shop splice (accomplished using a CJP groove weld in a butt joint). The use of longitudinal web stiffeners is generally limited to girders with very deep webs, but in such bridges, this detail would be difficult to avoid. See Figure 28.

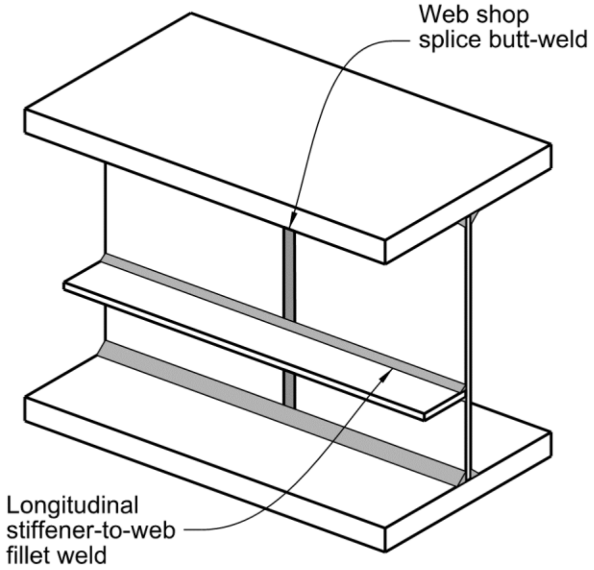


Figure 28. Intersection of a fillet-welded longitudinal web stiffener with a web shop splice using a CJP groove weld in a butt joint.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses. As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.

Condition 2: A high degree of constraint, preventing local yielding. At their juncture, the longitudinal stiffener prevents local through-thickness yielding of the web to some degree, but the constraint is biaxial, not triaxial. Thus, this detail would receive a score of 0.5 in this category.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. This condition is not present in this type of detail. There is no obvious crack-like or notch-like geometry (no discrete cut-outs or notches). There is also very little chance of a "hidden" plane of discontinuity in the web shop splice. The CJP groove welds in butt joints used to accomplish shop splices of webs are easily accomplished, since these types of shop splices are typically performed in the flange and web plates prior to their being welded together into a full plate girder. These welds are also subjected to thorough inspection and testing, providing a high level of assurance of quality. There is a possibility of a plane of discontinuity in the T-joint of the longitudinal stiffener and the web due to incomplete fusion between the fillet welds, but such a plane of discontinuity would be oriented parallel to the flow of primary tension stress in the longitudinal stiffener and the girder. Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 13:

Table 13. CIF evaluation scorecard for the intersection of a fillet-welded longitudinal web stiffener with a web shop splice accomplished using a CJP groove weld in a butt joint.

ITEM	**SCORE**
1. Tensile/Residual Stress	1.0 (low)
2. Degree of Constraint	0.5 (biaxial)
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category B detail (in the location away from the longitudinal stiffener termination) per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1 and 5.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

7.2 INTERSECTION OF A CONTINUOUS LONGITUDINAL WEB STIFFENER WITH A GIRDER WEB AND A DISCONTINUOUS TRANSVERSE WEB STIFFENER

Longitudinal web stiffeners often intersect both the girder web and also transverse web stiffeners, transverse connection plates, or bearing stiffeners. Various details have been used at the points of intersection of the three orthogonal structural elements. In this case, the longitudinal web stiffener is continuous and the transverse web stiffener is interrupted or discontinuous. This is the preferred detailing for this situation in general, and certainly for cases where the intersection is subjected to tension or stress reversal. See Figure 29, which shows detailing similar to that presented in Table 6.6.1.2.4-1 of the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

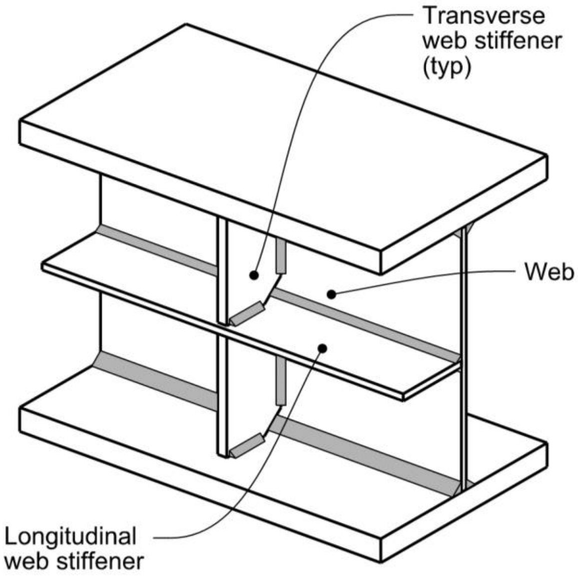


Figure 29. Intersection of a continuous longitudinal web stiffener with a girder web and a discontinuous transverse web stiffener.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** At their juncture, the longitudinal web stiffener and the transverse web stiffener prevent local through-thickness yielding of the web. However, a constraint-relief gap is provided by means of the copes of the stiffener; this provides relief of what might otherwise have been triaxial constraint of the web at the location of high tensile stresses in the web and the flange. For this example, it is assumed that the constraint-relief gaps are adequately sized, so at any given position the constraint is only biaxial. Thus, this detail would receive a score of 0.5 in this category. However, if the constraint-relief gaps were not large enough, this detail would receive a score of 1.0 in this category.
>
> ***Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress.*** There is no planar discontinuity approximately perpendicular to the primary flow of stress in this detail. This is a critical concept; since the longitudinal web stiffener is continuous (as are the girder web and flanges) and the transverse web stiffener is interrupted, there is no discontinuity in the primary flow of tensile stress in the members loaded in tension (i.e., the longitudinal stiffeners, the girder web, and the girder flanges). Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 14:

Table 14. CIF evaluation scorecard for the intersection of a continuous longitudinal web stiffener with the girder web and a discontinuous transverse web stiffener.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial) to 1.0 (high) depending on the width of the constraint-relief gaps
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 to 2.0 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category C' detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1 and 4.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

7.3 COPED AND WELDED INTERSECTION OF A DISCONTINUOUS LONGITUDINAL WEB STIFFENER WITH A GIRDER WEB AND A CONTINUOUS TRANSVERSE WEB STIFFENER

Consider next a modified version of the case illustrated in Section 7.2, a case where the longitudinal web stiffeners are interrupted or discontinuous and the transverse web stiffeners are continuous. In this case, also assume that the longitudinal web stiffeners are connected to the transverse web stiffeners with fillet welds. For new designs, Table 6.6.1.2.4-1 of the AASHTO BDS (2017a) (23 CFR 625.4(d)(1)(v)) only permits this type of detailing for cases where the intersection is always subjected to compression, and only at bearing stiffeners. However, this type of detailing may be found in existing structures. See Figure 30. For the purposes of this evaluation, assume that this detail is in an existing structure and is subjected to tension or stress reversal.

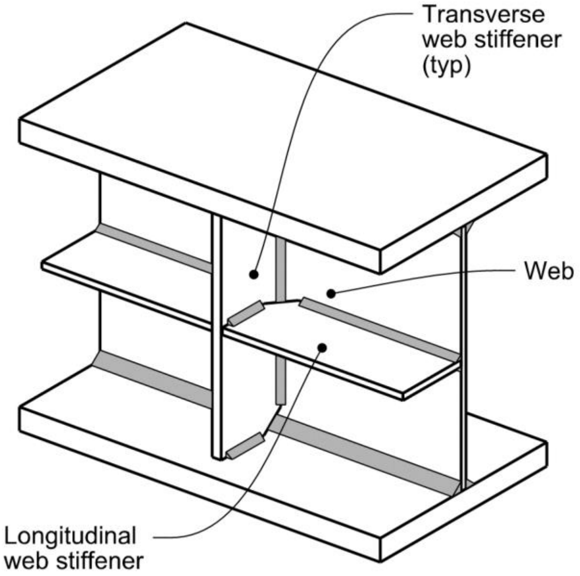


Figure 30. Coped and welded intersection of a discontinuous longitudinal web stiffener with a girder web and a continuous transverse web stiffener.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF. Again, for the purposes of this evaluation, assume that this detail is in an existing structure and is subjected to tension or stress reversal.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** At their juncture, the longitudinal web stiffener and the transverse web stiffener prevent local through-thickness yielding of the web. Constraint-relief gaps are provided by means of the copes of the stiffener; this provides some relief of what might otherwise have been triaxial constraint of the web at the location of high tensile stresses in the web and the flange. The width of these gaps (which would be related to the size of the cope and the sizes and detailing of the welds attaching the longitudinal web stiffeners and the transverse web stiffeners to the girder webs) are a critical parameter. If the gaps at any given position, measured between the weld toes or ends, are sufficiently wide enough to permit through-thickness yielding of the web the constraint would only be biaxial, and the degree of constraint being imposed would not be severe. But if gaps are too narrow, such that they do not provide sufficient relief of the constraint, the gaps could act more like a crack-like or notch-like discontinuity than constraint-relief gaps. Thus, this detail would receive a score of 0.5 in this category if the constraint-relief gaps are sufficiently sized, but would receive a score of 1.0 if the constraint-relief gaps were not large enough.
>
> ***Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress.*** In this case, it is likely that a planar discontinuity approximately perpendicular to the primary flow of tensile stress exists. The fillet welds connecting the longitudinal web stiffener to the transverse web stiffener are likely subject to incomplete fusion, creating a planar discontinuity parallel to the transverse web stiffener. Such a plane would be approximately perpendicular to the primary flow of tensile stress in the longitudinal stiffener. Furthermore, as mentioned above, if the constraint-relief gap is narrow, it may act more like a crack-like or notch-like discontinuity than a constraint-relief gap. Thus, this detail would receive a score of 1.0 for the planar discontinuities perpendicular to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 15:

Table 15. CIF evaluation scorecard for a coped and welded intersection of a discontinuous longitudinal web stiffener with a girder web and a continuous transverse web stiffener.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial) to 1.0 (triaxial) depending on the width of the constraint-relief gaps
3. Planar Discontinuity	1.0 (perpendicular)
TOTAL	**2.5 to 3.0 (high susceptibility to CIF)**

If this detail occurred in an existing structure and had adequately sized constraint-relief gaps, its score of 2.5 would result in a categorization of "may have high susceptibility to CIF," and further evaluation of the structure could be undertaken to inform the decision about whether to implement some type of retrofit to reduce the level of susceptibility to CIF. Alternately, a conservative decision could be made to implement a retrofit without further evaluation. From a fatigue standpoint, this would be a category C detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1, 4.1, and 5.4 as adjusted by Eq. 6.6.1.2.5-4 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

One way to reduce susceptibility to CIF in a detail like this would be to detail the longitudinal stiffener as continuous and interrupting the transverse stiffener (similar to the example in Section 7.2 of this guideline).

7.4 CONTINUOUSLY WELDED INTERSECTION OF A DISCONTINUOUS LONGITUDINAL WEB STIFFENER WITH A GIRDER WEB AND A CONTINUOUS TRANSVERSE WEB STIFFENER

Consider next another modified version of the case illustrated in Section 7.2, where the longitudinal web stiffeners are interrupted or discontinuous and the transverse web stiffeners are continuous. This is a poor detail and its use is not recommended, but such details may be found in older existing bridges. In this case, also assume that the longitudinal web stiffeners are connected to the transverse web stiffeners with continuous fillet welds. For new designs, Table 6.6.1.2.4-1 of the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)) only permits this type of detailing in cases where the intersection is always subjected to compression; e.g., at intersections with bearing stiffeners. See Figure 31. This type of detailing could exhibit elevated susceptibility to CIF if subjected to tension or stress reversal (per the evaluation below). This type of detailing may be subjected to such conditions in existing structures.

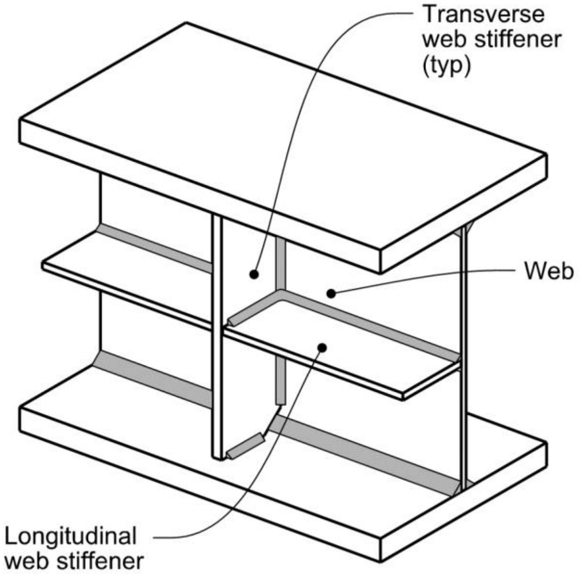


Figure 31. Continuously welded intersection of a discontinuous longitudinal web stiffener with a girder web and a continuous transverse web stiffener.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF. Remember, for the purposes of this evaluation, assume that this detail is in an existing structure and is subjected to tension or stress reversal.

Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses. As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.

Condition 2: A high degree of constraint, preventing local yielding. At their juncture, the longitudinal web stiffener and the transverse web stiffener prevent local through-thickness yielding of the web. No constraint-relief gaps are provided, so a high degree of triaxial constraint would be expected. Thus, this detail would receive a score of 1.0 in this category.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. In this case, it is likely that a planar discontinuity approximately perpendicular to the primary flow of tensile stress exists. The fillet welds connecting the longitudinal web stiffener to the transverse web stiffener are likely subject to incomplete fusion, creating a planar discontinuity parallel to the transverse web stiffener. Such a plane would be approximately perpendicular to the primary flow of tensile stress in the longitudinal stiffener. Thus, this detail would receive a score of 1.0 for the planar discontinuities perpendicular to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 16:

Table 16. CIF evaluation scorecard for a continuously welded intersection of a discontinuous longitudinal web stiffener with a girder web and a continuous transverse web stiffener.

ITEM	**SCORE**
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	1.0 (triaxial)
3. Planar Discontinuity	1.0 (perpendicular)
TOTAL	**3.0 (high susceptibility to CIF)**

From a fatigue standpoint, this would be a category C' detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1, 4.1, and 5.4, as adjusted by Eq 6.6.1.2.5-4 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

One way to reduce susceptibility to CIF in a detail like this would be to detail the longitudinal stiffener as continuous and interrupting the transverse stiffener, with appropriate coping provided (similar to the example in Section 7.2 of this guideline).

7.5 GAPPED INTERSECTION OF A DISCONTINUOUS LONGITUDINAL WEB STIFFENER WITH A GIRDER WEB AND A CONTINUOUS TRANSVERSE WEB STIFFENER

Next consider a further modified version of the case illustrated in Sections 7.3 and 7.4, again a case where the longitudinal web stiffener is interrupted or discontinuous and the transverse web stiffener is continuous. However, in this case, assume that the longitudinal web stiffeners are not connected to the transverse web stiffeners, but instead that there are gaps between the ends of the longitudinal web stiffeners and the transverse web stiffeners. Further assume that these gaps are narrow, say less than ¼ inch wide. See Figure 32. This type of detailing could exhibit elevated susceptibility to CIF if subjected to tension or stress reversal (per the evaluation below). **This type of detailing should not be used,** but may be found, and subjected to such conditions, in existing structures. For the purposes of this evaluation, assume that this detail is in an existing structure and is subjected to tension or stress reversal; in some older designs the longitudinal stiffener was extended into the tension region of the web where it did not contribute to the stability of web.

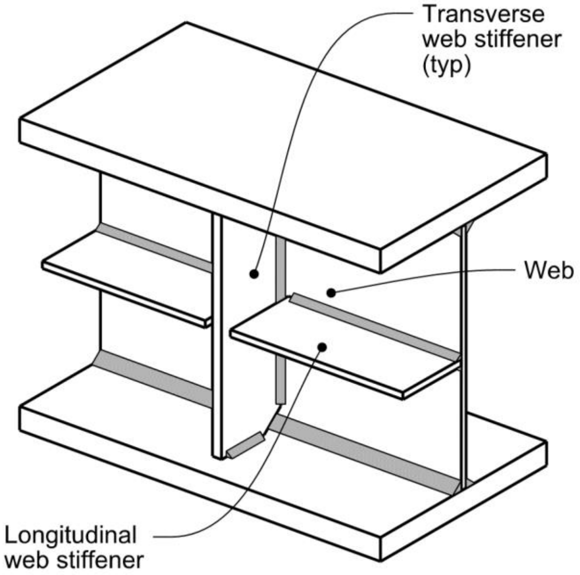


Figure 32. Gapped intersection of a discontinuous longitudinal web stiffener with a girder web and a continuous transverse web stiffener.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF. Remember, for the purposes of this evaluation, assume that this detail is in an existing structure and is subjected to tension or stress reversal.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** At their juncture, the longitudinal web stiffener and the transverse web stiffener prevent local through-thickness yielding of the web. The critical parameter in this detail is the width of the constraint-relief gaps (the gaps between the ends of the longitudinal web stiffeners and the transverse web stiffeners), as measured between the weld toes or ends. For this example, it is being assumed that the gaps, measured between the weld toes or ends, are not sufficiently wide enough to permit through-thickness yielding of the web. Consequently, the gaps actually act more like a crack-like or notch-like discontinuity than constraint-relief gaps. Thus, this detail would receive a score of 1.0.
>
> ***Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress.*** In this case, the narrow gaps (assumed to be ¼ inch wide) between the ends of the longitudinal web stiffeners and the transverse web stiffeners definitely represent crack-like or notch-like planes of discontinuity approximately perpendicular to the primary flow of tensile stress in the longitudinal web stiffeners and the web. Thus, this detail would receive a score of 1.0 for the planar discontinuities perpendicular to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 17:

Table 17. CIF evaluation scorecard for a gapped intersection of a discontinuous longitudinal web stiffener with a girder web and a continuous transverse web stiffener.

ITEM	**SCORE**
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	1.0 (triaxial)
3. Planar Discontinuity	1.0 (perpendicular)
TOTAL	**3.0 (high susceptibility to CIF)**

From a fatigue standpoint, the performance of this detail has been shown by Pass et al. (1983) and Platten (1980) to be worse than that of an E' detail per AASHTO BDS Table 6.6.1.2.3-1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

This detail is conceptually very similar to the “Hoan Bridge detail” and would be subject to an elevated susceptibility to CIF unless sufficiently wide constraint-relief gaps were provided.

One way to reduce susceptibility to CIF in a detail like this would be to detail the longitudinal stiffener as continuous and interrupting the transverse stiffener, with appropriate coping provided (similar to the example in Section 7.2 of this guideline).

Furthermore, it is noteworthy that this type of detailing would exhibit extremely poor fatigue performance and the terminations of the longitudinal stiffener-to-web fillet welds in this case would be classified as Category E or E' details per the provisions of Table 6.6.1.2.3-1 of the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

7.6 INTERSECTION OF A CONTINUOUS LATERAL CONNECTION PLATE WITH A GIRDER WEB AND A DISCONTINUOUS TRANSVERSE WEB STIFFENER

Lateral connection plates (i.e., the horizontally oriented gusset plates used to connect lateral bracing systems to the girders) are sometimes located in positions where they intersect transverse web stiffeners, transverse connection plates, or bearing stiffeners. These situations occur largely in older structures, where the lateral connection plates would frame into the girder web at some distance away from the flanges. For example, Figure 33 shows detailing presented in Table 6.6.1.2.4-2 of the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)). This type of detailing provides inefficient, indirect load paths. Modern designs typically use details where the lateral bracing frames directly into the girder flanges or into lateral connection plates that are attached to the flanges rather than into the girder webs, providing a more direct load path.

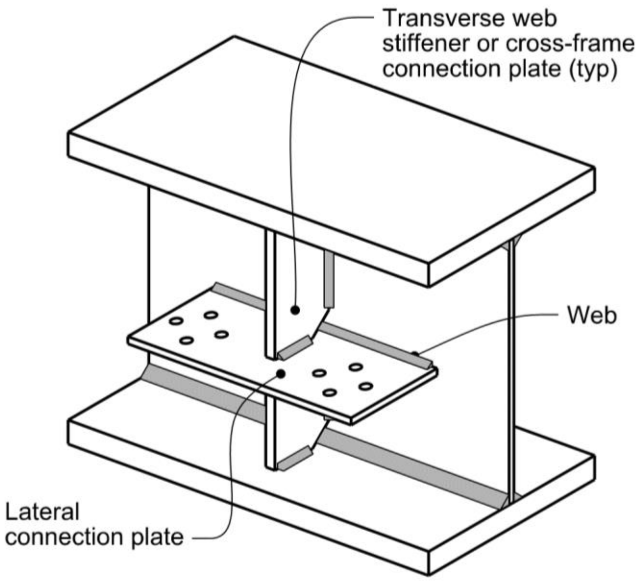


Figure 33. Intersection of a continuous lateral connection plate with the girder web and a discontinuous transverse web stiffener.

For the purposes of evaluating susceptibility to CIF, this case is very similar to the case of the intersection of a continuous longitudinal web stiffener with an interrupted or discontinuous transverse web stiffener (described in Section 7.2). The main difference is that the lateral connection plate has lateral bracing members attached to it. Those lateral bracing members, if loaded in tension, could impose a larger orthogonal stress on the web (exacerbating the constraint of the web).

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal due, to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** At their juncture, the lateral connection plate and the transverse web stiffener prevent local through-thickness yielding of the web. Furthermore, the lateral bracing members attached to the lateral connection plate, if loaded in tension, could impose a larger orthogonal stress on the web (exacerbating the constraint of the web). However, a constraint-relief gap is provided by means of the copes of the stiffener; this provides relief of what might otherwise have been triaxial constraint of the web at the location of high tensile stresses in the web and the flange. The key parameter here is the size of the constraint-relief gaps. If the gaps, measured between the weld toes or ends, are sufficiently wide enough to permit through-thickness yielding of the web, at any given position the constraint would only be biaxial, and the degree of constraint being imposed would not be severe. But if gaps are too narrow, such that they do not provide sufficient relief of the constraint, the gaps actually act more like a crack-like or notch-like discontinuity than constraint-relief gaps. Thus, this detail would receive a score of 0.5 in this category if the constraint-relief gaps are sufficiently sized, but would receive a score of 1.0 if the constraint-relief gaps were not large enough.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. There is no planar discontinuity approximately perpendicular to the primary flow of stress in this detail. This is a critical concept; since the lateral connection plate is continuous (as are the girder web and flanges) and the transverse web stiffener is interrupted or discontinuous, there is no discontinuity in the primary flow of tensile stress in the members loaded in tension (i.e., the longitudinal stiffeners, the girder web, and the girder flanges). Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 18:

Table 18. CIF evaluation scorecard for the intersection of a continuous lateral connection plate with a girder web and a discontinuous transverse web stiffener.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial) to 1.0 (triaxial) depending on the width of the constraint-relief gaps
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 to 2.0 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category C' detail at the transverse stiffener per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 3.1 and 4.1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)), a category E detail at the terminations of the lateral connection plate per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 6.1 (AASHTO, 2017a), and a category C detail in the attachment of the lateral connection plate to the web per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 6.4 and 5.4 as adjusted by Eq. 6.6.1.2.5-4 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

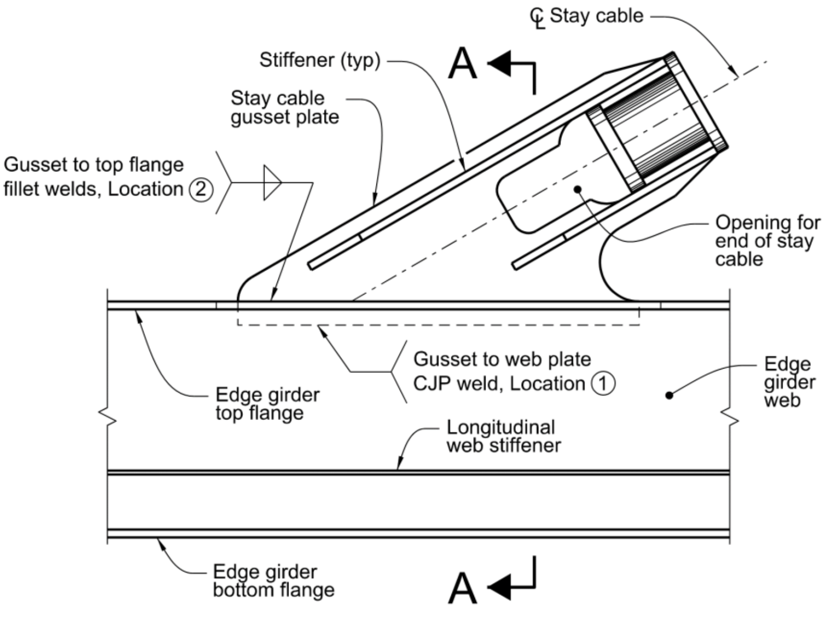
This particular case could be modified by reconfiguring the detail to have continuous transverse web stiffeners, with discontinuous lateral connection plates that are notched to fit around the transverse web stiffeners. The lateral connection plate would be fillet-welded to the transverse web stiffener (similar to the case illustrated in Section 7.3). The evaluation of the resulting detail would conclude that it was subject to a high susceptibility to CIF if the detail is subjected to net tension or stress reversal, similar to the conclusion for the detail illustrated in Section 7.3). The fatigue categorization of this detail would be fairly complicated. The connection of the transverse stiffener to the flange would be considered a Category C' fatigue detail per the provisions of Condition 4.1 of Table 6.6.1.2.3-1 of the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)). Without a transition radius in the connection plate, the terminations of the fillet welds attaching the lateral connection plate to the web would be considered Category E details per Description 6.1. For evaluating fatigue of the lateral connection plate itself, the detail would be considered a Category C as adjusted by Eq. 6.6.1.2.5-4, per Description 6.4, which refers back to Description 5.4. This detail is presented in Table 6.6.1.2.4-2 of the AASHTO BDS (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)), for use in cases where it is not practical to attach the lateral connection plate to a flange, the lateral connection plate is placed on the same side of the web as the transverse web stiffener, and the detail is subjected to compression; e.g., at the intersection with a bearing stiffener. However, this type of detailing provides inefficient, indirect load paths. Modern designs typically use details where the lateral bracing frames directly into the girder flanges or into lateral connection plates that are attached to the flanges rather than into the girder webs, providing a more direct load path

If this particular case was further modified by omitting the welded connection of the lateral connection plates to the transverse web stiffeners (similar to the case illustrated in Section 7.5), the resulting detail would essentially be the "Hoan Bridge detail." Such a detail would be subject to an elevated susceptibility to CIF unless sufficiently wide constraint-relief gaps were provided.

7.7 STAY CABLE ANCHORAGE CONNECTION TO AN I-SHAPED STEEL EDGE GIRDER

To illustrate the CIF evaluation procedure for a less common type of steel bridge detail, consider a bridge type more complicated than a typical girder-type steel bridge. Cable-stay bridges often use of unique connection details where the stay cables are anchored or otherwise attached to the rest of the bridge structure. Of particular interest in the context of evaluating susceptibility to CIF might be details connecting structural steel stay cable anchorages to structural steel deck system members.

Imagine a cable-stay bridge in which the deck system features steel edge girders and steel floor beams and a concrete deck. Assume the stay cables are anchored to steel edge girders using a projecting gusset plate detail. In this detail, a steel gusset plate might be attached to the edge girder by means of a complete joint penetration butt weld of the gusset plate to the girder web, accomplished through a slot in the top flange of the edge girder. The gusset plate might also be fillet-welded to the edge girder top flange along its sides. The slot might extend longer than the gusset plate on both ends and the ends of the slot might be left open past the leading and trailing edges of the gusset plate. See Figure 34, Figure 35, and Figure 36. The edge girder top flange and gusset plate might also have shear connectors that are eventually encased in deck concrete (not shown in the figures).



* Shear studs and reinforcement not shown for clarity

Figure 34. Elevation view of attachment of stay cable anchorage gusset plate to I-shaped steel edge girder.

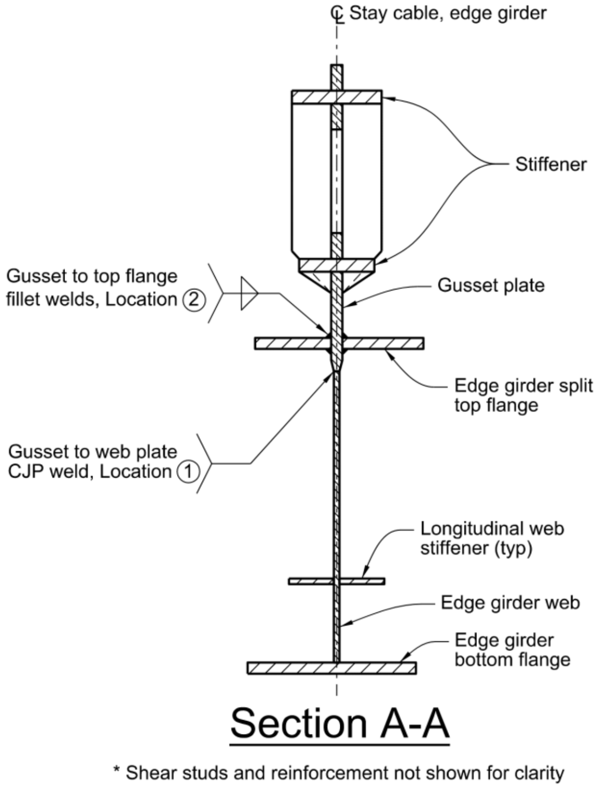


Figure 35. Section view of attachment of stay cable anchorage gusset plate to I-shaped steel edge girder.

Many aspects of this cable anchorage detail might warrant evaluation for structural performance, in terms of strength, serviceability, fatigue, etc. Each of those evaluations is very important, but this discussion focuses on only one of those many structural evaluations – an evaluation of susceptibility to CIF.

For the purposes of this example, several simplifying assumptions are made in the interests of clearly illustrating the application of the CIF evaluation procedure to a complex steel detail. Some of these assumptions may be debatable, depending on the specific nature of the actual structure being evaluated; the reader is encouraged to lay aside those debates, accept the assumptions, and focus on the illustration of the CIF evaluation procedure.

For simplicity, it is assumed that the connection of the structural steel details to the concrete deck (via shear connectors) has no impact on the susceptibility to CIF. This is a reasonable and conservative assumption. Such connections may provide composite action for the steel edge girder, or may improve the performance or serviceability of the deck system, but realistically these connections would do little or nothing to prevent or arrest a fracture in the structural steel framing.

For this example, conservatively assume that the top flange and top of the web of the edge girder are in tension or subjected to stress reversal. Assume that the edge girder is subjected to negative moment at the stay cable anchorage and that the cable-stay system is not introducing a sufficient net compression in the deck system to fully overcome, under all loading conditions, the tension in the top flange and top part of the web of the edge girder. This assumption is dependent on the overall structural behavior of the bridge, which is beyond the scope of this example. Assuming this stress condition is conservative for the purposes of evaluating the susceptibility of this detail to CIF.

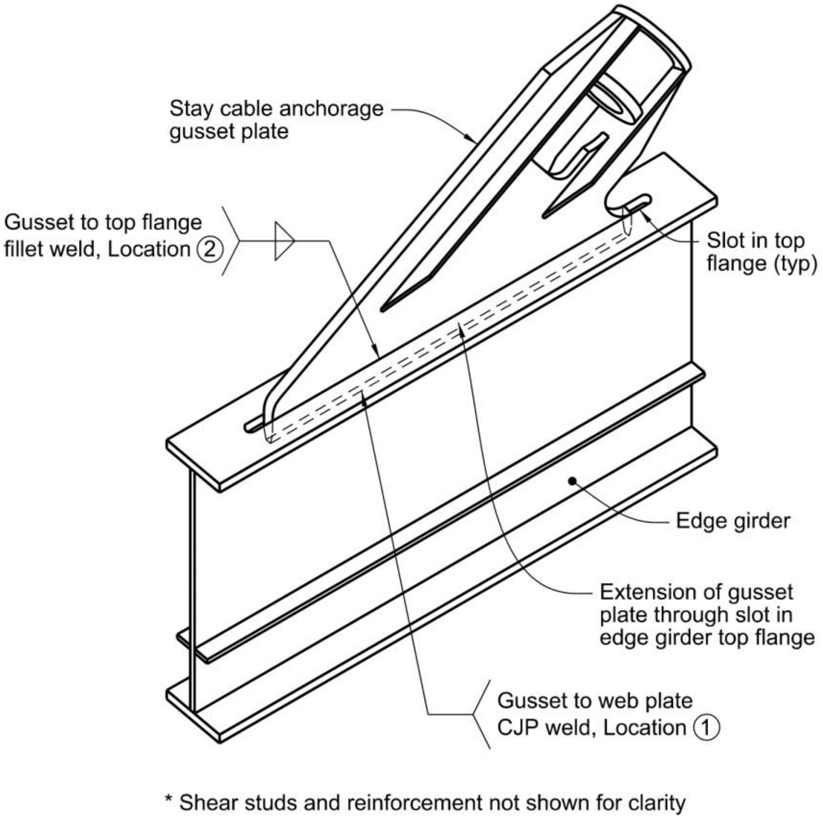


Figure 36. Isometric view of attachment of stay cable anchorage gusset plate to I-shaped steel edge girder.

With these assumptions in place, evaluate the detail with regard to the three conditions associated with elevated susceptibility to CIF. Perform the evaluation at two distinct locations: 1) at the complete joint penetration butt weld connection of the stay cable anchorage gusset plate and the edge girder web; and 2) at the fillet-welded connection of the gusset plate to the edge girder top flange.

At location (1), the complete joint penetration butt weld connection of the stay cable anchorage gusset plate and the edge girder web:

> ***Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses.*** As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.
>
> ***Condition 2: A high degree of constraint, preventing local yielding.*** At the complete joint-penetration butt weld connection of the gusset plate to the edge girder flange, there are no external welded attachments. As a result, there is no externally introduced constraint and, at that specific location, the detail would receive a score of 0.0 for constraint.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. As has been suggested elsewhere in this report, a properly designed, detailed, executed, and inspected complete joint penetration weld can reasonably be assumed to be free of significant discontinuities; thus, the complete joint penetration butt weld connecting the gusset plate to the edge girder web can be assumed to be free of planar discontinuities and would receive a score of 0.0 for this condition.

A summary of the evaluation is provided in Table 19:

Table 19. CIF evaluation scorecard for the intersection of stay cable anchorage gusset plate with cable-stay bridge edge girder, at location of complete joint penetration butt weld connection of gusset plate to edge girder web.

ITEM	**SCORE**
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.0 (no constraint)
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.0 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category D or E detail per AASHTO BDS Table 6.6.1.2.3-1, Description 6.3 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

At location (2), the fillet-welded connection of the gusset plate to the edge girder top flange:

Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses. As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.

Condition 2: A high degree of constraint, preventing local yielding. As the gusset plate passes through the edge girder top flange, the fillet welds connecting the gusset plate to the top flange plate create a condition of biaxial constraint. Thus, at that specific location, the detail would receive a score of 0.5 for constraint.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. Four fillet welds are used to connect the gusset plate to the edge girder top flange at the point where the gusset plate passes through the top flange. At that location, there are two potential planar discontinuities, one on each side of the gusset plate, both parallel to the gusset plate. For tensile loading in the gusset plate these planar discontinuities are parallel to the primary flow of tensile stress in the gusset plate, which is through the plane of the gusset plate along the axis of the stay cable. For tensile loading in the edge girder top flange these planar discontinuities are also parallel to the primary flow of tensile stress in the edge girder top flange, which is through the plane of the top flange along the longitudinal axis of the edge girder. Since these planar discontinuities are parallel to the primary flow of tensile stress in both of these primary elements (the gusset plate and the edge girder top flange), this detail would receive a score of 0.0 for this condition at this location.

A summary of the evaluation is provided in a scorecard format in Table 20:

Table 20. CIF evaluation scorecard for the intersection of stay cable anchorage gusset plate with cable-stay bridge edge girder at location of connection of gusset plate to edge girder top flange with four fillet welds.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial)
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 (low susceptibility to CIF)**

From a fatigue standpoint, there is no directly comparable detail in the AASHTO BDS Table 6.6.1.2.3-1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)). From various perspectives, various components of this particular detail might be considered:

- category C per AASHTO BDS Table 6.6.1.2.3-1, Description 1.3 (AASHTO, 2017a);
- category D per AASHTO BDS Table 6.6.1.2.3-1, Description 1.5 or 3.3 (AASHTO, 2017a); or
- category B, C, D, or E, depending on the radius provided where the gusset plate is attached to the edge girder web, per AASHTO BDS Table 6.6.1.2.3-1, Description 6.1 or 6.2 (AASHTO, 2017a).

CHAPTER 8 - EXAMPLE EVALUATIONS OF OTHER COMMON DETAILS

Many other details are used in steel transportation structures. Two examples are discussed in this section. Each detail is subjected to the evaluation procedure described in Section 4.1.

8.1 INTERSECTION OF RIB-TO-DECK PLATE WELDS WITH RIB-TO-FLOOR BEAM AND FLOOR BEAM-TO-DECK PLATE WELDS IN ORTHOTROPIC STEEL DECKS

Orthotropic steel decks often involve details featuring intersecting welds, such as the intersection of rib-to-deck plate welds with rib-to-floor beam welds and floor beam-to-deck plate welds. In bridges with orthotropic steel decks, details like this would be difficult to avoid. Consider the case of continuous ribs with fitted and fully fillet-welded floor beams. See Figure 37.

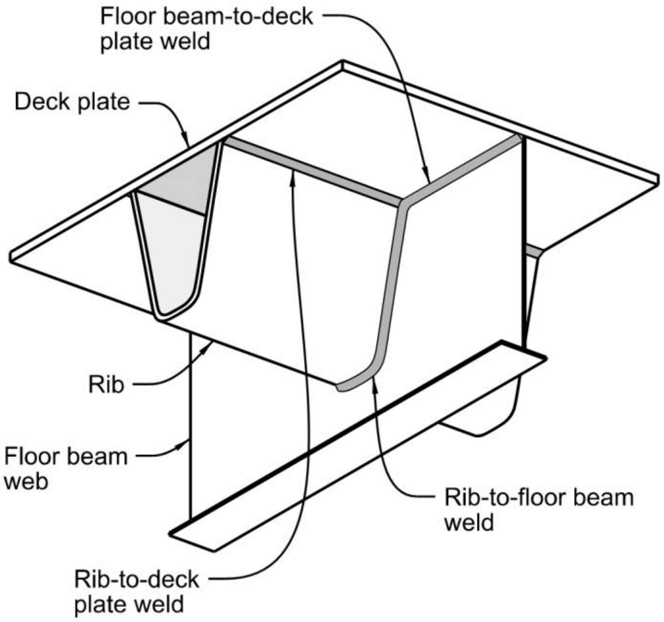


Figure 37. Intersection of a rib-to-floor beam fillet weld with a floor beam-to-deck plate fillet weld and a rib-to-deck plate fillet weld.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses. As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.

Condition 2: A high degree of constraint, preventing local yielding. At their juncture, various elements of an orthotropic steel deck would prevent local through-thickness yielding of other elements to some degree. In some locations, the constraint is probably triaxial; for example, the rib walls are constrained by both the fitted and fillet-welded floor beams and by the deck plate. However, the degree of constraint in that location is expected to be relatively low since all of the elements involved are quite thin. It is reasonable to assign this detail a score of 0.5 in this category.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. This condition is not met in this type of detail. There is no obvious crack-like or notch-like geometry (no discrete cut-outs or notches). There is also very little chance of a "hidden" plane of discontinuity in the welds. Fillet welding is often used for connection of relatively thin elements, including the deck plate, the ribs, and the floor beam webs. The likelihood of lack of joint penetration in these connections is relatively low. Even if there were a plane of discontinuity, that plane would be oriented parallel to the flow of primary tension stress in the girder in most locations. Thus, this detail would receive a score of 0.0 for the planar discontinuities parallel to the primary flow of tensile stress.

A summary of the evaluation is provided in Table 21:

Table 21. CIF evaluation scorecard for the intersection of a rib-to-floor beam fillet weld with a floor beam-to-deck plate fillet weld and a rib-to-deck plate fillet weld.

ITEM	SCORE
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial)
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 (low susceptibility to CIF)**

From a fatigue standpoint, this would be a category C detail per AASHTO BDS Table 6.6.1.2.3-1, Descriptions 8.5 and 8.6 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)).

8.2 INTERSECTION OF COLUMN-TO-BASE PLATE COMPLETE JOINT PENETRATION GROOVE WELDS WITH STIFFENER-TO-BASE PLATE FILLET WELDS AND STIFFENER-TO-COLUMN FILLET WELDS

Although not specifically found in steel bridges on a regular basis, there are many instances of stiffener-to-column fillet welds intersecting stiffener-to-base plate fillet welds and column-to-base plate complete joint penetration groove welds in other transportation structures, such as high mast light poles, steel columns, arch ribs, etc. See Figure 38.

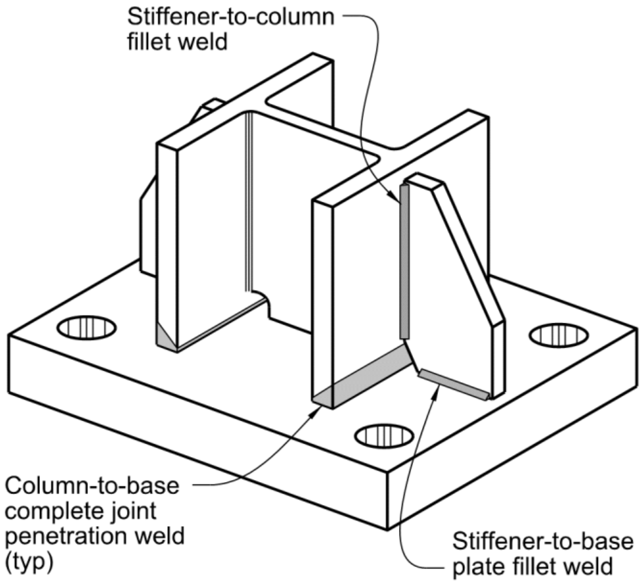


Figure 38. Intersection of column-to-base plate complete joint penetration groove welds with stiffener-to-base plate fillet welds and stiffener-to-column fillet welds.

Evaluate the detail for the three conditions associated with elevated susceptibility to CIF.

Condition 1: A sufficiently high net tensile stress, including consideration of residual stresses. As noted in Section 4.1, it is reasonable to assume that this condition is present in any and all members or components subjected to a tensile stress or stress reversal, due to the presence of potentially high levels of tensile residual stresses. Thus, this detail would receive a score of 1.0 in this category.

Condition 2: A high degree of constraint, preventing local yielding. At their juncture, the base plate would prevent local through-thickness yielding of the column flanges and the stiffeners to some degree. In some locations, the constraint could be triaxial. For example, the flanges of the column are constrained by both the base plate and the stiffener. At that same location, the column flange is also constrained by the column web immediately opposite of the stiffener. However, a constraint-relief gap is provided by means of the cutouts in the column web at the bottom of the column. This provides relief of the constraint at the location of high tensile stresses in the column flanges. The key parameter here is the size of the constraint-relief gaps. If the gaps, measured between the weld toes or ends, are sufficiently wide enough to permit through-thickness yielding of the web, at any given position, the constraint would only be biaxial, and the degree of constraint being imposed would not be severe. But if gaps are too narrow, such that they do not provide sufficient relief of the constraint, the gaps actually act more like a crack-like or notch-like discontinuity than constraint-relief gaps. Thus, this detail would receive a score of 0.5 in this category if the constraint-relief gaps are sufficiently sized, but would receive a score of 1.0 if the constraint-relief gaps were not large enough.

Condition 3: A planar discontinuity approximately perpendicular to the primary flow of tensile stress. Theoretically, there are no crack-like or notch-like planes of discontinuity approximately perpendicular to the primary flow of tensile stress in the column itself. In practicality, an imperfection in the CJP welds attaching the column flanges to the base plate might constitute such a plane of discontinuity, but CJP welds are typically subjected to a high level of fabrication inspection.

> In addition, there is not a high degree of constraint at the location of those CJP welds. There could be a plane of discontinuity approximately perpendicular to the primary flow of tensile stress at the bottom of the stiffeners. At that location there could potentially be incomplete fusion between the fillet welds attaching the stiffener to the base plate, especially if the stiffener is relatively thick. Therefore, this detail would receive a score of 0.0 for the lack of planar discontinuities in the CJP-welded connections of the flanges to the base plate, but a score of 1.0 for the planar discontinuities perpendicular to the primary flow of tensile stress in the fillet-welded connections of the stiffeners to the base plate.

A summary of the evaluation for the intersection of the column-to-base plate complete joint penetration groove welds is provided in Table 22:

Table 22. CIF evaluation scorecard for the intersection of column-to-base plate complete joint penetration groove welds.

ITEM	**SCORE**
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial) to 1.0 (triaxial) depending on the width of the constraint-relief gaps
3. Planar Discontinuity	0.0 (not present)
TOTAL	**1.5 (low susceptibility to CIF), assuming the constraint-relief gaps are wide enough (3.0 if not)**

A summary of the evaluation for the intersection of the stiffener-to-base plate fillet welds is provided in Table 23Table 22:

Table 23. CIF evaluation scorecard for the intersection of stiffener-to-base plate fillet welds.

ITEM	**SCORE**
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial) to 1.0 (triaxial) depending on the width of the constraint-relief gaps
3. Planar Discontinuity	1.0 (perpendicular)
TOTAL	**2.5 (potentially high susceptibility to CIF), assuming the constraint-relief gaps are wide enough (3.0 if not)**

A summary of the evaluation for the intersection of the stiffener-to-column fillet welds is provided in Table 24Table 22:

Table 24. CIF evaluation scorecard for the intersection of stiffener-to-column fillet welds.

ITEM	**SCORE**
1. Tensile/Residual Stress	1.0 (high)
2. Degree of Constraint	0.5 (biaxial) to 1.0 (triaxial) depending on the width of the constraint-relief gaps
3. Planar Discontinuity	0.0 (parallel)
TOTAL	**1.5 (low susceptibility to CIF), assuming the constraint-relief gaps are wide enough (2.0 if not)**

The score of 2.5 would suggest that such detailing might have a high susceptibility to CIF. However, similar types of detailing are presented in the AASHTO *LRFD Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals* (AASHTO, 2017c) (23 CFR 625.4(d)(1)(ix), and have exhibited reasonable fatigue performance in experimental testing (Koenigs et al., 2003, Stam, 2009) . Furthermore, the authors are not aware of reports of CIF occurring in service in high mast poles with this type of detailing. This may be due to the ability of the stiffener to yield locally just above the fillet-welded connection or to the presence of adequate constraint-relief gaps. This case illustrates the difficulty associated with trying to “quantify” the degree of constraint present in a complicated detail.

From a fatigue standpoint, this detail is not addressed in AASHTO BDS Table 6.6.1.2.3-1 (AASHTO, 2017a) (23 CFR 625.4(d)(1)(v)). See the AASHTO *LRFD Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals* (AASHTO, 2017c) (23 CFR 625.4(d)(1)(ix) for related discussion.

CHAPTER 9 - MEASURES TO MITIGATE ELEVATED SUSCEPTIBILITY TO CIF

9.1 INSPECTION, REPAIR, AND RETROFIT OF DETAILS SUBJECT TO ELEVATED SUSCEPTIBILITY TO CIF IN EXISTING BRIDGES

The inspection of steel bridges with details that may be susceptible to CIF is covered in the BIRM (Ryan et al., 2012) and the FHWA/NHI *Fracture Critical Inspection Techniques for Steel Bridges – Participant Workbook* (Ryan et al., 2010). Both of these documents provide discussion of how to inspect and evaluate various details.

The evaluation, repair, and retrofit of bridges with details that are subject to an elevated susceptibility to CIF is covered by Russo et al. (2016), *Design and Evaluation of Steel Bridges for Fatigue and Fracture – Reference Manual*, and Connor and Lloyd (2017), *Maintenance Action to Address Fatigue Cracking in Steel Bridge Structures, Proposed Guidelines and Commentary*.

Russo et al. (2016) focuses more on design and detailing of new bridges, but the fundamental concepts discussed can be applied to the evaluation of existing in-service bridges as well.

Connor and Lloyd (2017) discuss suggested repair and retrofit actions for details in existing bridges that may be susceptible to CIF. For example, the report addresses a common detail susceptible to CIF in older bridges – the lateral connection plate detail, sometimes referred to as a “Hoan-like detail.” Repair and retrofit strategies for other CIF-susceptible details are also presented.

9.2 AVOIDING OR MITIGATING DETAILS SUBJECT TO ELEVATED SUSCEPTIBILITY TO CIF IN NEW DESIGNS

When preparing a design of a new steel bridge, it is important, as well as relatively easy, to avoid details that would otherwise be subject to an elevated susceptibility to CIF. Details under consideration can be assessed using the evaluation procedure presented in Chapter 5. Details found to be subject to an elevated susceptibility to CIF can be redesigned or reconfigured to mitigate one or more of the three conditions associated with elevated susceptibility to CIF. The basic concepts, listed in order of importance and ease of implementation, are as follows:

1. If it the intersection of welded elements in areas of net tension or stress reversal is unavoidable, detail longitudinal structural elements (the elements oriented parallel or approximately parallel to the primary flow of tensile stress) as continuous and interrupt transverse elements;
2. If possible, avoid details that introduce a high degree of constraint to steel elements subjected to net tension or stress reversal, particularly details that would introduce a high degree of triaxial constraint;
3. If the intersection of welded elements in areas of net tension or stress reversal is unavoidable and the longitudinal structural element cannot be detailed as continuous, one way to mitigate the potential to develop high levels of stress triaxiality might be to provide appropriate constraint-relief gaps.

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REVISION AND ERRATA LIST - JUNE 2023

The following list represents corrections incorporated in the June 2023 edition of the Guide to Evaluating Details for Susceptibility to Constraint-Induced Fracture.

- Corrected figure numbering throughout.
- Corrected section references throughout.
- Added new reference (Ref 20).

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