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Identification of Bridges with Fracture-Prone Details

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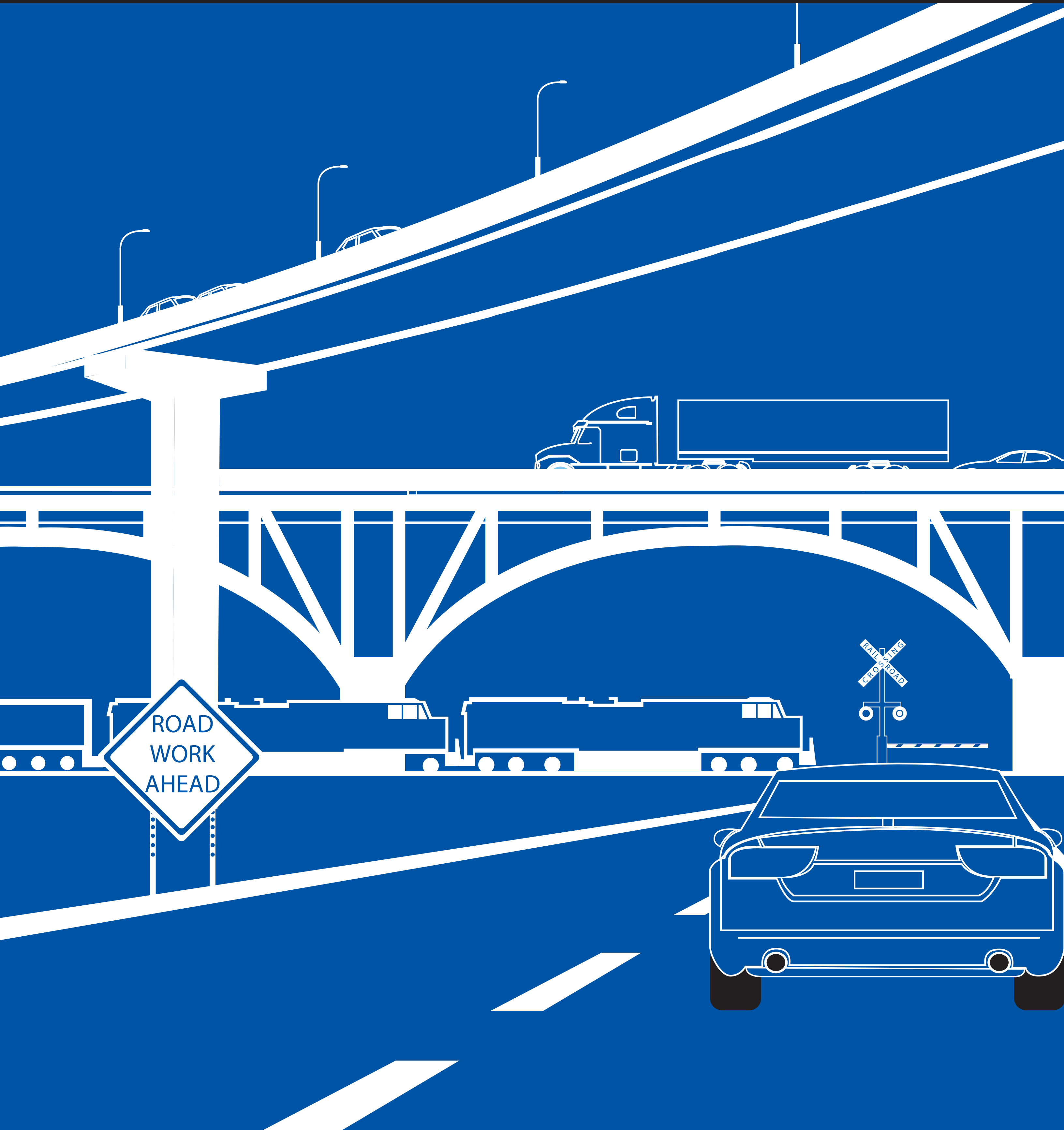

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University of Kentucky

Research Report
KTC-19-35/SPR18-553-1F

Identification of Bridges with Fracture-Prone Details

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16. Abstract
Welded steel girder bridges can contain details that can high welding and service stresses and are termed constraint-induced fractures (CIF). The Kentucky Transportation Cabinet has steel bridges with weld details known to cause CIFs whose girders have experienced fracture events. The Cabinet's bridge inventory was reviewed and additional candidate bridges with potential CIF details were identified. A review of bridge plans and pictures along with follow-up field investigations pinpointed bridges with CIF details that warrant up-close (i.e., arm's length) inspections. Several uninspected bridges were identified as candidates for inspection to determine if they contain CIF details. Guidance is provided to help the Cabinet prioritize bridge inspections for CIF details and on repair actions for mitigating potentially problematic ones.

17. Key Words
bridges, constraint, cracking, details, fractures, girders, inspections, steel, welding

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Executive Summary

The Kentucky Transportation Cabinet (KYTC) is responsible for maintaining roughly 1,100 steel bridges. Some of bridges in this inventory employ welded steel girders with details that make them prone to constraint-induced fractures (CIFs). These unstable brittle fractures develop without warning and can severely damage or even sever parts of girders, impacting the structural integrity of a bridge. This phenomenon was first observed on the I-794 Hoan Bridge in Milwaukee, Wisconsin, in December 2000. After several trucks passed over the bridge, the deck on an approach span sagged, prompting its closure. Inspections of the bridge revealed that two of the three girders supporting the deck had completely severed and found a large crack in the third girder. A follow-up investigation concluded that the cracks had appeared suddenly and were not present until the fracture event. Based on these findings, the FHWA Federal Highway Administration released a technical advisory in 2001 that catalogues which weld details were problematic. The agency suggested that state departments of transportation consider evaluating their steel bridges to determine if any had problematic details and offered guidance for addressing them.

In 2012, major fractures were discovered in girders of both the northbound and southbound I-75 bridges over Lynn Camp Creek in Whitley County. The bridges were repaired but no investigation was conducted. In 2014, a second major fracture was found in the northbound bridge. Researchers at the Kentucky Transportation Center (KTC) investigated this failure. While a very small fatigue crack was found at the origin, the girder web failed by unstable brittle fracture and KTC researchers could not rule out as a contributing failure mechanism.

In 2017, KYTC asked the Center to identify welded steel bridges in its inventory with fracture-prone weld details. Selection criteria were established to limit the data set to only welded girder bridges (the type that contained only CIF details). An initial screening returned a list of 345 candidate bridges. Researchers evaluated these structures to determine if they have potentially problematic CIF details. The assessment consisted of searching for pictures and plans in BrM files and conducting site evaluations of bridges where filed data was absent. KTC then compiled a list of 45 bridges with potentially problematic CIF details. Researchers identified another 55 bridges they either could not access or which possessed steel spans even though they were labeled in BrM as being of a different material type.

This report provides criteria KYTC inspectors can use to assess the remaining 55 bridges to determine 1) if they possess CIF details, and 2) if those details are sufficiently problematic to warrant follow-up actions (i.e., mitigation). Cabinet staff will need to perform these inspections at arm's length to measure the spacing between attachment welds. If this measurement is below a critical value, they would be categorized as being potential sources of CIFs. Guidance is also provided to help KYTC prioritize bridge inspections for CIF details and repair actions to mitigate potentially problematic ones.

1. Introduction

1.1 Background

The Kentucky Transportation Cabinet (KYTC) is responsible for the inspection and maintenance of approximately 1,100 steel bridges. The average age of these structures exceeds 45 years. Many of them may possess weld details that render them susceptible to fatigue cracking or contribute to unstable brittle failures (i.e., constraint-induced fractures [CIFs]). Both phenomena can disable bridges and require expensive repairs. In nearly every case, problematic weld details have been identified and retrofit measures (if needed) are available.

This project was initially intended to address potential fatigue and CIF problems by reviewing the Cabinet's existing information on at-risk bridges and identifying structures with problematic weld details so they could receive special attention during normal inspection or even, where warranted, retrofitting to eliminate the threat of steel fractures on structural members. This work did not deal with potential structural steel cracking problems caused by structural impacts, field welding for repairs, utility encroachments, or potential materials problems (e.g., quenched-and-tempered steels).

At the initial project meeting, the KYTC Study Advisory Committee (SAC) and Kentucky Transportation Center (KTC) researchers determined a major unknown was the extent to which information needed for this project would be available in the Cabinet's Bridge Management software (BrM). This raised the possibility of KTC needing to conduct numerous onsite visual inspections to determine if problematic details were present on bridges. As such, the SAC and research team elected to defer work addressing potentially problematic fatigue-prone weld details (i.e., AASHTO Fatigue Categories E, E' and F) and focus only on identifying structures with CIF details.

1.2 Constraint-Induced Fractures

Structural welding involves the application of heat to melt electrodes and base metals to fuse them together. The heating and eventual cooling of the completed weldments creates residual stresses in the welds and adjacent steel plates. When multiple welds are oriented perpendicular to each other and in close proximity (or even in contact) they can place the affected region in a triaxial tension state of stress. That inhibits the ability of the steel in that region from deforming plastically to redistribute residual and applied stresses.

If those stresses are sufficiently high in tension with complex tensile stress components due to welding (usually a localized condition), a crack can initiate (pop-in) rapidly releasing built-up strain energy. If the amount of strain energy available exceeds the resisting force to create additional new crack surface area in the steel, the crack can run until it either fractures the weldment (e.g. a steel girder) or the available strain energy in the piece is insufficient to create additional fracture surface leading to crack arrest. The former can occur when the temperature of the steel is below its ductile-to-brittle transition temperature. In that case, the energy required to create new crack surface area is low. The result is a rapid unstable brittle cleavage fracture that shows little deformation. The latter can occur when a crack travels into a portion of the weldment with low tensile stresses that don't provide a sufficient strain energy release or when the energy necessary to create new crack surface area in the steel is greater than the available strain energy. Such events are termed constraint-induced fracture (CIF).

In some cases, steel girder weldments incorporate stiffening elements (vertical and horizontal) or attachments such as shelf plates welded to their webs. In the past, those details were not considered problematic and little attention was paid to their design or execution in fabrication shops.

The seminal event related to CIFs was the I-794 Hoan Bridge fracture in Milwaukee, Wisconsin, on December 13, 2000. At that time, Winter conditions were present and the temperature was below freezing. Early that morning several trucks crossed the bridge, causing the third span of the southbound approach to sag. The bridge was promptly closed, and inspectors found that two of the three girders supporting the roadway were completely fractured along with a 30-inch long crack in the bottom portion of the web of the third girder (Figures 1, 2).

A follow-up investigation concluded that those fractures originated at the gusset plate area connecting lateral bracing to the girder webs (1). Two of these attachment details were involved in the fractures (Figure 3). Previously, the Wisconsin Department of Transportation (DOT) had detected arrested cracks at other approach span locations ranging in length from 6 to 36 inches. Those previously detected cracks were initially attributed to fatigue. A typical mock-up of similar lateral bracing connections is shown in Figure 4. With the lateral bracing removed, the mock-up shown in

Figure 3 reveals that the gusset plate is slotted allowing it to straddle a vertical stiffener (also termed a transverse connector (Figure 5). Both the vertical stiffener and the gusset are attached to the girder web by fillet welds. The gusset slot is slightly wider than the vertical stiffener to accommodate its thickness plus the legs (width) of the fillet welds. This creates a narrow gap between the stiffener and gusset that acts as a stress riser (the red arrow in Figure 5). This attachment type is now referred to as the *Hoan Detail*, but it does not address every weld detail that can produce CIFs. In some cases, the gap in the aforementioned slot may be eliminated by welding. That has proven problematic as well (2).

Significant findings from the Wisconsin investigation are summarized below:

- All of the crack surfaces showed only brittle, cleavage fractures (including the earlier ones that had arrested in the webs at other locations and had been initially attributed to fatigue). There were no signs of fatigue or ductile tearing. This was the first known incident in the US where an in-service bridge fracture involved only brittle crack initiation and growth. Others may have pre-dated the Hoan Bridge fracture, but they were either not recognized as brittle fractures or the findings were not publicized.
- All fractures originated in the web plate at the joint where the lower lateral bracing system framed into the web. The initiation site was located in the gap between the gusset plate and the stiffener plate.
- There was no evidence of fatigue cracking prior to fracture initiation. This indicates that there was no damage prior to the sudden fracture. Even a fracture critical inspection would not have uncovered the fracture.
- Web material properties met standards for A36 steel. Toughness met the 2001 AASHTO requirements for Zone 2, fracture critical use.
- Flange material properties met the standards for A588 steel. Toughness met the 2001 AASHTO requirements for Zone 2, non-fracture critical use.
- Stresses due to the sum of all loads (including the truck passages that caused girder failure) were probably within acceptable design limits for the bridge.
- A narrow gap between the gusset plate and the transverse connection/stiffener plate created a local triaxial constraint condition and increased the stiffness in the web gap region at the fracture initiation site. This constraint prevented yielding and redistribution of the local stress concentrations in this region. As a result, the local stress state in the web gap was forced well beyond the materials' yield strength. Under triaxial constraint, the apparent fracture toughness of the material is reduced and brittle fracture can occur under service conditions where ductile behavior is normally expected.

In 2001, after the investigation was completed, the FHWA requested that DOTs identify all of their two- and three-girder bridges with similar attachment details. Shortly thereafter, the FHWA provided agencies with a technical advisory which explained the Hoan Bridge fracture event and provided inspection guidance and options to retrofit similar details to prevent brittle fractures (3). A key determinant of a problematic condition is when perpendicular fillet welds of web attachments are in close proximity (less than 1/4") or in contact.

Over time, several DOTs issued internal documents addressing CIF-prone details for agency personnel or consultants and local governments, sometimes along with agency policies for handling them (4, 5). The Illinois DOT circular letter 2010-09 provides illustrations of some CIF-prone details (Figures 6 and 7). Since 2000, several CIF-related fractures have affected several US bridges (Ref 2, 6).

In 2012, KYTC discovered fractures on both the southbound and northbound I-75 bridges over Lynn Camp Creek in Whitley County (Figures 8, 9). They are continuous welded-plate girder structures with four girder lines. The fractures occurred in the girder webs near the center of the longest (200 ft.) spans. It appeared that the factures emanated from potential CIF locations, similar to a detail shown in the Illinois DOT circular letter (see Figure 6, lower detail). The bridges were quickly repaired, however, there was no follow-up investigation. As the red arrow in Figure 9 indicates, the fillet welds attaching the horizontal and vertical stiffeners were in contact, indicating that a CIF fracture was possible.

In June 2014 another fracture was found on the same girder (No. 2) of the northbound bridge that experienced a fracture event in 2012 one panel over (Figure 10). The 2014 fracture occurred in the same location as the 2012 fracture. Unlike the 2012 events, by the time this fracture was detected it had advanced into the lower flange and periodic monitoring revealed that it was growing by fatigue (Figure 11). KTC analyzed the girder at the time of its fracture (7).

Pieces of the web and stiffeners were removed straddling the fracture, where the horizontal and vertical stiffeners were in close proximity. A fracture surface at that location indicated the web had experienced an unstable brittle fracture (Figure 12, yellow arrows) which originated near the termination of the horizontal stiffener-to-web fillet weld. Close study with a scanning electron microscope revealed a thumbnail-shaped fracture origin which KTC determined was a fatigue crack that subsequently drove the unstable brittle failure when it reached a critical size of only ~ 5 mm wide x 1 mm deep (Figure 13). While fatigue cracking precipitated the unstable brittle failure in the web, the presence of a CIF detail and small size of the fatigue crack at the point of instability led KTC researchers to speculate that constraint-induced fracture might have played a key role. It is unknown whether the 2012 events similarly involved fatigue cracking or simply brittle CIF fractures from crack pop-in.

1.3 Work Plan

This research had three objectives:

- Identify KYTC welded steel bridges with fracture-prone weld details.
- Determine methods to retrofit/mitigate the likelihood of fracture for specific detail types.
- Help the Cabinet develop a method for prioritizing those bridges for retrofitting/repair to eliminate/mitigate those details.

The objectives were addressed through the following tasks:

- Perform a literature search to identify fatigue and fracture-prone weld details and retrofits/mitigation actions.
- Review of the KYTC steel bridge inventory and categorization of bridges according to KYTC-established criteria.
- Obtain bridge plans for high-priority welded steel bridges and identify problematic weld details.
- Prepare a list of bridges that are considered high-priority candidates for retrofit/mitigation actions, noting the problem details, locations on the bridge, and associated retrofit/mitigation action.
- Prepare a final report documenting Tasks 1-4 and a prioritized list of bridges, fatigue and fracture-prone details, and potential retrofits/mitigation actions.

2. Work Addressing Study Tasks

KTC researchers performed a literature search to identify papers, technical articles, and reports related to fatigue and fracture-prone weld details as well as retrofit/mitigation actions. These documents were reviewed and relevant items are cited in this report.

A September 2018 review of KYTC's steel bridge inventory (conducted using BrM) found approximately 1,100 steel bridges. Researchers then contacted the Cabinet to obtain access to BrM files. Given the time and funding constraints under which all bridge evaluations needed to be completed, the SAC let KTC researchers establish criteria to reduce the number of candidate bridges. The following criteria were used to cut down the number of bridges that would be evaluated:

- Steel bridges with potential welded construction (i.e., those built after 1955)
- Deck girder steel bridges
- Steel bridges with spans > 80' to 360'
- Steel bridges on Interstates, US routes, or Parkways

The 1955 start date for steel bridges with welded construction was chosen based on a conversation with a past Division of Bridges Director employed at the Kentucky Bureau of Highways in the 1970s. CIF details that were problematic and/or of national concern are limited to those in deck girder spans. Spans from 80' to 360' were of sufficient length to capture all KYTC girder bridges and eliminate spans that were likely made from rolled beams. The SAC requested that researchers limit their work to bridges on major routes (i.e., interstate, US and parkways).

Applying these criteria lowered the number of candidate structures for review to 346. The initial effort to identify bridges with CIF-type details consisted of a paper review. Researchers accessed BrM files to examine the structures via pictures and plans. Based on this review, they eliminated 205 structures. A portion of the remaining 141 bridges were identified as possibly having potentially problematic details. As previously noted, a key determinant of a problematic condition is when perpendicular fillet welds of web attachments are in close proximity (less than 1/4") or in contact. The other bridges lacked relevant information in their BrM files. It was determined that all 141 bridges should be inspected to ascertain whether they had CIF details (in some cases) and whether the CIF details were problematic.

Bridges were visually inspected in the field by KTC to determine if they possessed CIF-type details. After BrM site inspections were completed, 45 bridges were identified as having potentially problematic CIF details due to apparent weldment designs for gussets or the apparent proximity between horizontal and vertical stiffeners that might relate to design, detailing, or shop fabrication (Table 1). Fifty-five (55) of the 141 bridges could not be accessed during field inspections; therefore, KTC could not determine if CIF details were present (Table 2). On 41 bridges KTC did not find problematic details and removed them from further consideration.

3. Recommendations

Based on its efforts, KTC researchers are advancing the following recommendations:

1. KYTC should perform follow-up inspections of selected bridges.

The Cabinet needs to inspect the 45 steel bridges with potentially problematic CIF details as well as the 55 bridges KTC could not access. In addition to those, KTC researchers learned at the end of the work on this project that the BrM lists bridge material types by the one that has the most spans (or longest span). Further inspection revealed 10 bridges on the SAC-prioritized routes (interstate, US, and parkway) classified as other bridge types (e.g. prestressed concrete), but containing steel spans (Table 3). These bridges will also need to be inspected by KYTC. In total, 110 bridges require some type of inspection.

The inspection process can be divided into two stages:

Stage 1) CIF detail identification (bridges in Tables 2 and 3), and
Stage 2) Determine if CIF details are problematic (all bridges in Table 1 and bridges in Tables 2 and 3 with CIF details).

To identify CIF details (Stage 1), the Illinois DOT pictures are an excellent reference (Figures 6 and 7). Those images should be provided to KYTC inspectors to assist them in identifying CIF details. To determine if a CIF detail is problematic (Stage 2), the gaps between web attachment fillet welds/weld terminations need to be measured for gussets and stiffeners. If the distance between those welds are 1/4" or less *or* the welds are touching, KYTC should consider retrofitting the details to prevent brittle fracture.

Due to variability in shop fabrication, the existence of problematic CIF details can vary along girders. Unless the design of the attachments has sufficient spacing between welds that obviously precludes problems, the weld gaps should be measured, requiring arm's-length access to the details (Figures 14 and 15). In case of the Hoan Detail (Figure 14), the cope at the base of the gusset slot does not prevent the gusset-to-web fillet weld from coming into close proximity of the vertical stiffener-to-web fillet weld. The large slot in the gusset (Figure 15) does not prevent those perpendicular welds from being in close proximity either, and a hands-on measurement of the gap between them is necessary to determine if they are problematic.

Some welded attachment/stiffener details may not exactly replicate the classical Hoan Detail. Nevertheless, they are CIF details and need to be evaluated. The gusset in Figure 16 is bolted to a bracket that is fillet welded to the web. The bracket fillet weld is in close proximity to the vertical stiffener-to-web weld. In addition, the bracket is fillet welded to the vertical stiffener. Two weld gaps need to be evaluated in that case (see the arrow in Figure 16). If KYTC inspectors encounter questionable details such as this, they can contact KTC researchers for assistance in assessing them.

KYTC should develop a short training program for inspectors that will teach them how to identify CIF details on welded steel bridges and perform measurements to identify when CIF details are problematic. KTC can assist in this effort if requested.

2. Recommendations for prioritizing inspections of bridges with potentially problematic CIF details.

KTC ranked the 45 bridges with potentially problematic CIF details for inspections is determined by three priorities.

- Fracture-Critical Bridges (17 identified)
    - Fracture-critical bridges should receive priority for CIF detail inspections regardless of other factors. Currently, it is not believed that CIF events on steel bridges are related to accumulated damage. They may be related to a combination of temperature (which affects steel toughness) and peak loads, although the Hoan investigation seemed to indicate otherwise.

- Bridge Loading
  - ADT values for the 45 bridges range from 2,085 to 86,651 vehicles per day with ADTT values being most relevant. This factor is somewhat paradoxical as low ADT bridges may be heavy haul routes such as the Bush Road Overpass fracture in 2016 that might be more conductive to single event fractures that appear characteristic to CIF events (8). Conversely, if small fatigue cracks can interact with constraint to promote unstable brittle fractures, ADT (or ADTT) may be an important factor.

- Route Carried (Interstates – 26, US routes – 11, and Parkways – 8)
  - Bridges on Interstate routes should be prioritized over bridges on the other two route types (all other things being equal).

3. Mitigation actions are recommended if weld gaps are < 1/4” or the perpendicular welds are touching. Where cracks emanate from CIF details, crack mitigation should be promptly undertaken on the balance of the CIF details where the weld gaps are < 1/4”. The same recommendation holds for any problematic CIF details on fracture-critical bridges.

The simplest form of mitigation is to place check holes adjacent to the weld gaps as this intercepts any cracks that might emerge and prevents large-scale damage to girders (Figures 17 and 18). Other recommendations for potential repairs were provided by the FHWA in the 2001 Technical Advisory (3). These are:

- Retrofit options include hole drilling and/or grinding to separate the welds and eliminate the weld intersection. Great care should be exercised when choosing this option since widening the web gap can make the connection more flexible and increase its vulnerability to distortion-induced fatigue.

- Other options include complete removal of the lateral brace system and gusset plates, similar to the retrofit performed on the Hoan Bridge. This requires a detailed engineering analysis to determine if the lateral system is needed for performance of the structure. Relocating the lateral system attachment to the bottom flange can also be considered in cases where analysis shows the lateral system is required.

3. Conclusions

KTC researchers began this project by examining the Cabinet's inventory of 1,100 steel bridges. Ninety percent of those were eliminated from consideration as potential CIF candidates based upon age or size considerations. However, because KTC lacked the access equipment and funding to perform arm's length inspections, they could not verify if the 45 bridges with CIF details are in fact problematic or may be removed from consideration as brittle fracture risks. Another 55 were not addressed due limitations associated with documentation and access or KTC's lack of familiarity with the BrM bridge classification methodology. KYTC can review these bridges on a case-by-case basis with some emphasis recommended for any structures considered fracture-critical.

The original goal of this study was to address potential fracture problems in welded steel bridges related to CIF and fatigue-prone details. This report completes CIF portion of that work. KTC recommends that the Cabinet continue to identify bridges with fatigue-prone details. Note that that CIF details usually contain horizontal plate weld terminations that constitute Category E fatigue details. In addition to identifying bridges and problematic details, fatigue assessments could be performed to determine what risks those details pose. At KYTC's request, over the past 5 years, KTC has investigated three steel bridge fractures related to (potentially) CIFs and fatigue (both low- and high-cycle). Common factors underpinning those fractures were welding and the use of carbon structural steels. Troublingly, in each of these cases all of the steels involved met AASHTO charpy test requirements for Zone 2 redundant structures. Another issue of concern is the increasing average age of KYTC steel bridges, which currently stands at more than 45 years. Older bridges tend to have greater accumulated damage to the steel and are more likely to experience fatigue cracking.

In the US, girder fractures have not yet produced a total bridge collapse. This is due in part to a reserve of strength in the deck system. The I-794 Hoan Bridge incident was probably as close to a near collapse as any fracture event yet observed, including the I-79 Neville Island fracture of one girder of a two-girder system in 1977. Even with fractures in redundant structures, the cost of reactive maintenance is high and on an interstate routes (e.g., I-75) can result in significant delays for motorists. It will be worthwhile to follow through on KYTC CIF inspections and implement the fatigue portion of KTC's initial proposal.

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Tables

Table 1. Bridges with Potentially Problematic Constraint-Induced Fracture Details							
Interstate Bridges							
Bridge ID	**Facility Carried**	**Feature Intersected**	**District**	**County (CO #)**	**Year Built**	**Fracture Critical/ CIF Detail**	**ADT**
056B00266N	I-264 EB AND RAMP	US 31W	District 5	Jefferson (056)	1974	N *	86651
019B00045N	I-275 RAMP	Over I275WB-I471SB-RAMP F	District 6	Campbell (019)	1974	N *	82370
056B00161N	I-64	Shawnee Golf Course	District 5	Jefferson (056)	1962	Y *	81936
056B00281N	I-64 RAMP	Northwestern Pkwy	District 5	Jefferson (056)	1971	Y **	81936
056B00285N	I-64	Conrail, NE-ERN Pkwy	District 5	Jefferson (056)	1972	Y ***	72032
056B00293N	I-64	Old P and L RR (7-13 St)	District 5	Jefferson (056)	1976	Y ***	72032
059B00063L	I-275 WB	CSX RR-KY 17-Banklick CR	District 6	Kenton (059)	1977	N **	50864
059B00063R	I-275 EB	CSX RR-KY 17-Banklick CR	District 6	Kenton (059)	1977	N **	50864
019B00041L	I-275 WB	KY 8	District 6	Campbell (019)	1979	Y *	39572
019B00041R	I-275 EB	KY 8	District 6	Campbell (019)	1979	Y *	39572
021B00042L	I-71	Kentucky River	District 6	Carroll (021)	1967	Y **	23274
021B00042R	I-71	Kentucky River	District 6	Carroll (021)	1967	Y **	23274
063B00043L	I-75 NC	Laurel River	District 11	Laurel (063)	1969	Y **	21231
063B00043R	I-75	Laurel River	District 11	Laurel (063)	1969	Y **	21231
073B00120L	I 24 NC	Clarks River	District 1	McCracke n (073)	1975	N ***	19121
073B00120R	I-24	Clarks River	District 1	McCracke n (073)	1975	N ***	19121
118B00063L	I-75 NC	Lynn Camp Creek	District 11	Whitley (118)	1968	N ***	18188
118B00063R	I-75	Lynn Camp Creek	District 11	Whitley (118)	1968	N ***	18188
006B00048L	I-64-10 NC	Kendall Springs Rd &Slte C	District 9	Bath (006)	1967	N *	11765
006B00048R	I-64	Kendall Springs Rd &Slte C	District 9	Bath (006)	1967	N *	11765
022B00083L	I-64	L. Sandy River & KY 1910	District 9	Carter (022)	1971	Y ***	10577
022B00083R	I-64	Little Sandy River	District 9	Carter (022)	1971	Y ***	10577

103B00054L	I-64 NC	Bull Fork Crk & Road	District 9	Rowan (103)	1968	N *	10043
103B00054R	I-64	Bull Fork Crk & Road	District 9	Rowan (103)	1968	N *	10043
022B00095L	I-64	Tygarts Creek	District 9	Carter (022)	1969	N *	6512
022B00095R	I-64	Tygarts Creek	District 9	Carter (022)	1969	N *	6512

* Gusset plate
** Perpendicular stiffeners
*** Gusset plate and perpendicular stiffeners

Table 1. Cont. Bridges with Potentially Problematic Constraint-Induced Fracture Details

US Route Bridges

Bridge ID	Facility Carried	Feature Intersected	District	County (CO #)	Year Built	Fracture Critical/ CIF Detail	ADT
045B00049N	US-23	Tygarts Creek	District 9	Greenup (045)	1973	N *	10214
040B00028L	US-27	Kentucky River & Co Rd	District 7	Garrard (040)	1974	Y ***	9674
040B00028R	US-27	Kentucky River & Co Rd	District 7	Garrard (040)	1972	Y ***	9674
042B00212L	US-45	Mayfield Creek	District 1	Graves (042)	1980	N **	6742
042B00212R	US-45	Mayfield Creek	District 1	Graves (042)	1980	N **	6742
005B00027N	US-31E	Peter Creek Embayment	District 3	Barren (005)	1963	N *	5383
005B00025N	US-31E	Skaggs Creek Embayment	District 3	Barren (005)	1963	N *	5268
048B00110N	US-119	Poor FK Cumberland River	District 11	Harlan (048)	1975	N *	4497
091B00027N	US-68	Licking River	District 9	Nicholas (091)	1969	N ***	4100
016B00054N	US-231	W.H. Natcher Parkway	District 3	Butler (016)	1972	N *	2488
022B00077N	US-60	I 64	District 9	Carter (022)	1969	N *	2085

* Gusset Plate
** Perpendicular Stiffeners
*** Gusset Plate and Perpendicular Stiffeners

Table 1. Cont. Bridges with Potentially Problematic Constraint-Induced Fracture Details							
Parkway Bridges							
Bridge ID	**Facility Carried**	**Feature Intersected**	**District**	**County (CO #)**	**Year Built**	**Fracture Critical/ CIF Detail**	**ADT**
025B00055N	Mountain PKY NC	I-64	District 7	Clark (025)	1962	N *	13899
016B00061N	WN-9007	Green River	District 3	Butler (016)	1972	Y *	8873
090B00019L	Martha L. Collins PKY	Chaplin River	District 4	Nelson (090)	1965	N *	5841
090B00019R	Bg-9002	Chaplin River	District 4	Nelson (090)	1965	N *	5841
026B00082N	HR-9006	Red Bird River	District 11	Clay (026)	1973	N **	5306
100B00074L	Louis B. Nunn\Cumb. PKY	Fishing Creek	District 8	Pulaski (100)	1973	Y *	4507
100B00074R	LN-9008	Fishing Creek	District 8	Pulaski (100)	1973	Y *	4507
066B00052N	HR-9006	KY257-Mid-FK KY River-C504	District 11	Leslie (066)	1973	N **	4030

* Gusset Plate
** Perpendicular Stiffeners
*** Gusset Plate and Perpendicular Stiffeners

Table 2. Bridges Not Inspected by KTC that May Contain Constraint-Induced Fracture Details							
Interstate Bridges							
Bridge ID	**Facility Carried**	**Feature Intersected**	**District**	**County (CO #)**	**Year Built**	**Fracture Critical**	**ADT**
008B00052N	I-275	Ohio River	District 6	Boone (008)	1976	Y	39714
019B00037N	US 27	I 275	District 6	Campbell (019)	1974	N *	7212
019B00042N	I-275 RAMP	I471NB-I275EB-Ramps E&F	District 6	Campbell (019)	1974	N	79143
019B00043L	I-275 WB	I-471 N.B.	District 6	Campbell (019)	1974	N	41185
019B00043R	I-275 EB	I471NB & Ramp E Under Ramp D	District 6	Campbell (019)	1974	N	41185
024B00132L	I-24-10 NC	West Fork Red River	District 2	Christian (024)	1974	N	23020
024B00132R	I-24	West Fork Red River	District 2	Christian (024)	1974	N	23020
037B00052L	I-64 WB	Kentucky River	District 5	Franklin (037)	1963	Y **	25659
037B00052R	I-64 EB	Kentucky River	District 5	Franklin (037)	1963	Y **	25659

037B00053L	I-64 WB	US 60	District 5	Franklin (037)	1972	N	25659
037B00053R	I-64 EB	US 60	District 5	Franklin (037)	1972	N	19112
047B00133R	I-65	Rolling Fork River	District 4	Hardin (047)	1985	Y	32890
056B00056N	I-71 SB OFF RAMP	I-71 NB & I-264 Ramp	District 5	Jefferson (056)	1967	N	55318
056B00088N	I-265 SB OFF RAMP	Westport Rd (KY 1447)	District 5	Jefferson (056)	1970	N	68197
056B00191N	I-65	Jacob, Broadway, Gray St	District 5	Jefferson (056)	1960	N	84001
056B00264N	I-264 WB	US 31W	District 5	Jefferson (056)	1974	N	86651
056B00272N	I-264 RAMP	US 31W	District 5	Jefferson (056)	1974	N	86651
056B00274N	I-264 RAMP	US 31W	District 5	Jefferson (056)	1974	N	86651
056B00287L	I-265 SB	Westport Rd (KY 1447)	District 5	Jefferson (056)	1976	N	34099
056B00287R	I-265 NB	Westport Rd (KY 1447)	District 5	Jefferson (056)	1976	N	34099
056B00298N	I-64 RAMP 4	I64 Ramps 1/3 Main Market	District 5	Jefferson (056)	1975	Y	72032
056B00300N	I-64 RAMP	I-64 E/W And Main St	District 5	Jefferson (056)	1975	Y	72032
056T00916N	I-65 NB EXIT RAMP	I-64, I-65, Witherspoon	District 5	Jefferson (056)	2016	N	5250
056T00917N	I-65 NB RAMP	I-64E, Witherspoon, Ramps	District 5	Jefferson (056)	2016	N	5250
056T00918N	I-65S RMP TO I-64E	I-64 EB, I-65N Ramps	District 5	Jefferson (056)	2016	N	144000
056T00929N	RMP I-65S TO I-71N	Witherspoon, Adams, Rr	District 5	Jefferson (056)	2016	N	72000
059B00052L	I-275 WB	CSX RR-KY 177-Lickng River	District 6	Kenton (059)	1973	N	52750
059B00052R	I-275 EB	CSX RR-KY 177-Lickng River	District 6	Kenton (059)	1972	N	52750
059B00054L	I-275 WB	I-75 N&S-Ramps A-C-G-D	District 6	Kenton (059)	1971	Y	43613
059B00054R	I-275 EB	I-75 N&S-Ramps A-C-G-D	District 6	Kenton (059)	1971	Y	43613
059B00055N	I-75 RAMP	I275-I75-G&D Ramps	District 6	Kenton (059)	1971	Y	157708
059B00056N	I-75 RAMP	I275-I75-G&D Ramps	District 6	Kenton (059)	1971	Y	210707
059B00060N	I-275 RAMP	US 25 & US 42	District 6	Kenton (059)	1973	N	100559

059B00061N	I-275 RAMP	Ramp F (EB Entr. Ramp)	District 6	Kenton (059)	1973	N	101728
059B00072N	I-75 RAMP	Ramp Donaldson To I-75	District 6	Kenton (059)	1977	N	210707
073B00105L	I 24 NC	US 60	District 1	McCracken (073)	1972	N	22512
073B00105R	I-24	US 60	District 1	McCracken (073)	1972	N	22512

* Close inspection by KYTC is recommended to determine if plate is welded or bolted to girder
** Possible problems with horizontal and vertical stiffeners at arch of steel - Closer inspection by KYTC is recommended

Table 2. Cont. Bridges Not Inspected by KTC that May Contain Constraint-Induced Fracture Details							
US Route Bridges							
Bridge ID	**Facility Carried**	**Feature Intersected**	**District**	**County (CO #)**	**Year Built**	**Fracture Critical**	**ADT**
002B00007N	US-31E	Barren River Lake	District 3	Allen (002)	1963	N	4479
019B00037N	US 27	I 275	District 6	Campbell (019)	1974	N *	7212
036B00038R	US-23	Levisa Fork of Big Sandy	District 12	Floyd (036)	1973	N **	7026
048B00065N	US-119	KY 413 & Poor Fork of Cmbrld R.	District 11	Harlan (048)	1966	N	8275
073B00005R	US-60	Clarks River	District 1	McCracken (073)	1960	N	9207
098B00266N	US 52	Tug Fork	District 12	Pike (098)	1997	N	9800
112B00040N	US 421	Ohio River	District 5	Trimble (112)	2014	Y	8853

* Close inspection by KYTC is recommended to determine if plate is welded or bolted to girder
** Problematic details on four girders and appears to have many problematic Hoan details – Close inspection by KYTC is recommended

Table 2. Cont. Bridges Not Inspected by KTC that May Contain Constraint-Induced Fracture Details							
Parkway Bridges							
Bridge ID	**Facility Carried**	**Feature Intersected**	**District**	**County (CO #)**	**Year Built**	**Fracture Critical**	**ADT**
001B00063L	Louie B. Nunn PKY	Russell Creek	District 8	Adair (001)	1972	N	3506
001B00063R	LN-9008	Russell Creek	District 8	Adair (001)	1972	N	3506
003B00007L	BG Parkway	KY River	District 7	Anderson (003)	1965	Y **	9459

003B00007R	BG-9002	KY River	District 7	Anderson (003)	1965	Y **	9459
030B00085L	WN-9007	Wendell Ford Expressway	District 2	Daviess (030)	1972	N	4701
030B00085R	WN-9007	Wendell Ford Expressway	District 2	Daviess (030)	1972	N	4701
051B00072N	AU-9005	Green River	District 2	Henderson (051)	1971	Y **	9935
051B00073L	Audubon PKY NC	Pennyrile PKY	District 2	Henderson (051)	1970	N	4714
051B00073R	AU-9005	US 41	District 2	Henderson (051)	1970	N	4714
089B00093L	Wendell H Ford Wes	Green River	District 2	Muhlenberg (089)	1964	Y **	5088
089B00093R	WK-9001	Green River	District 2	Muhlenberg (089)	1963	Y **	5088
120B00030N	BG PKY - 9002	US 60	District 7	Woodford (120)	1965	N	21830

** Possible problems with horizontal and vertical stiffeners at arch of steel - Closer inspection by KYTC is recommended

Table 3. Bridges with Steel Spans Classified as Concrete Structures Not Inspected by KTC

Bridge ID	Facility Carried	Feature Intersected	District	County (CO #)	Year Built	Fracture Critical	ADT
022B00037N	US-60	Tygarts Creek	District 9	Carter (022)	1923	N	3221
034B00026N	US-27	New Circle Road	District 7	Fayette (034)	1967	N	74083
050B00035N	US-31W	Bacon Creek	District 4	Hart (050))	1933	N	2574
056T00912N	I-64 TO I-65SB Ramp	I-64 EB, Ramp, E. Witherspoon	District 5	Jefferson (056)	2016	N	10500
059B00044L	I-75 NC	11th-12th-Lewis In Covington	District 6	Kenton (059)	1960	N	79675
059B00044R	I-75	US25,KY1120,(11th,12th,L	District 6	Kenton (059)	1960	N	79675
105B00121L	I-75 South	NS (CO &TP) System	District 7	Scott (105)	1994	N	25877
105B00121R	I-75	NS (CO&TP) System	District 7	Scott (105)	1994	N	25877

Figures

Figure 1 The I-794 Hoan Bridge in Milwaukee, Wisconsin, after the girder fracture event (December 2000). Note the sage in the barrier wall and girder (arrow).

Figure 2 Complete girder fractures in two of the three approach span girders (arrows).

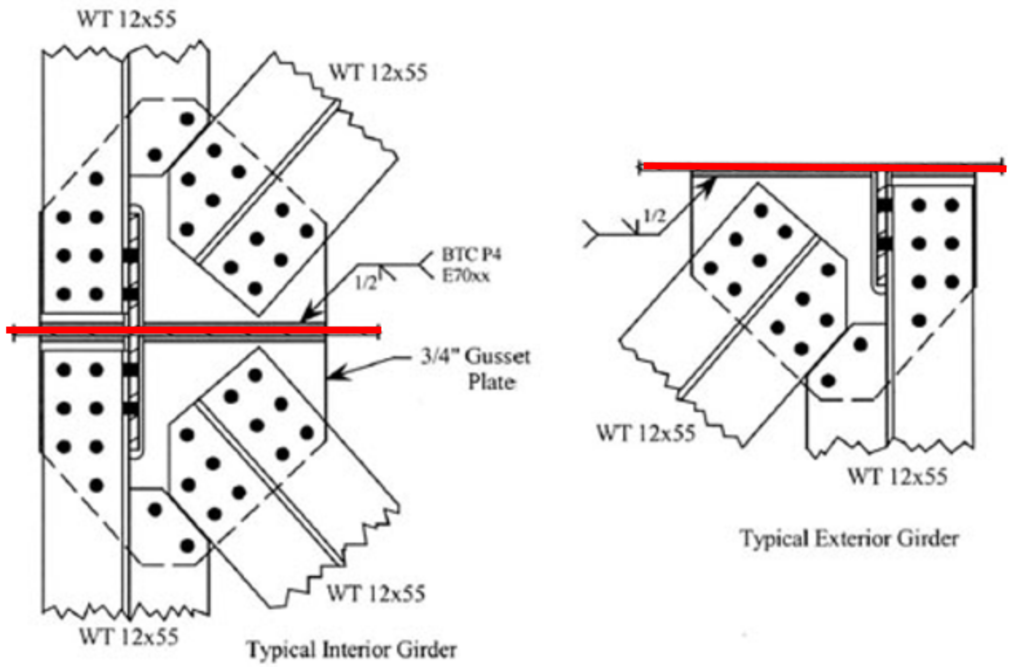

Figure 3 Plan views of girder attachment details of connections of girder webs (red lines) with lateral bracing - WT 12 x 55s (2).

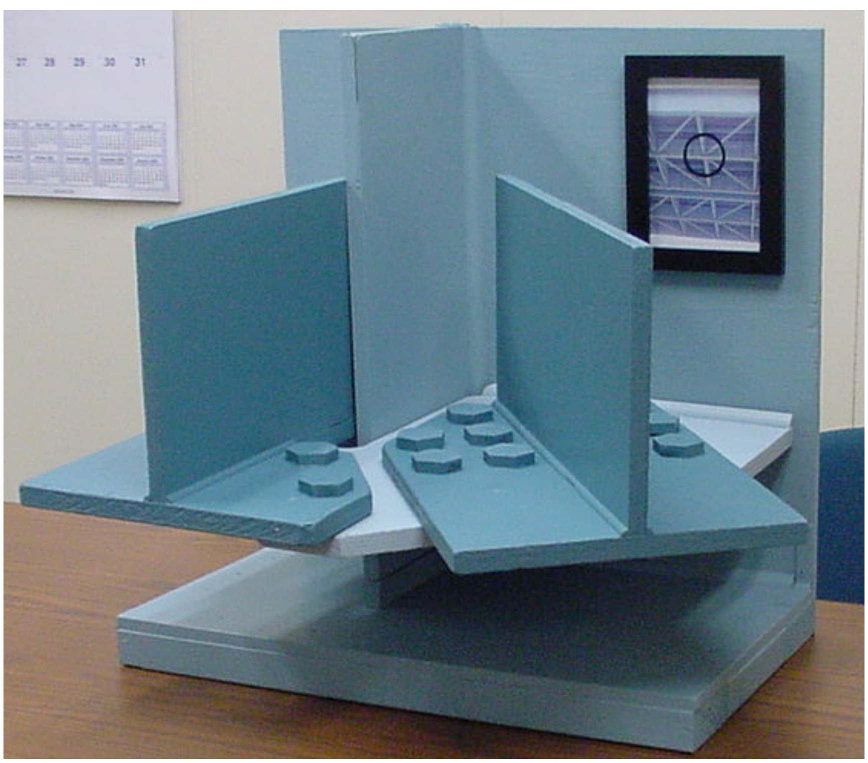

Figure 4 Mock-up of Hoan Bridge-type fracture detail (light green) showing lateral bracing attachments (green).

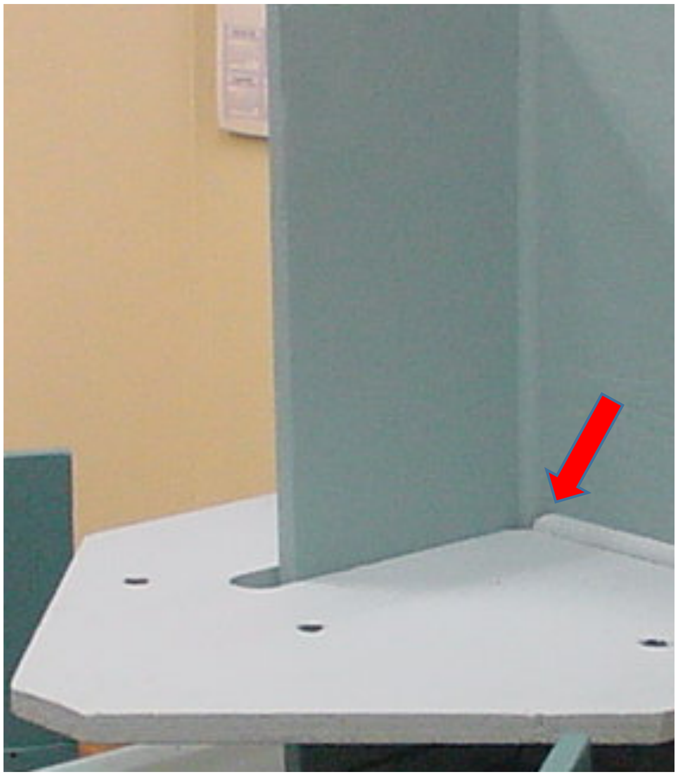

Figure 5 Mock-up of Hoan Bridge-type fracture detail (light green) with bracing removed. The problematic gap lies between the vertical stiffener and gusset plate fillet welds (arrow).

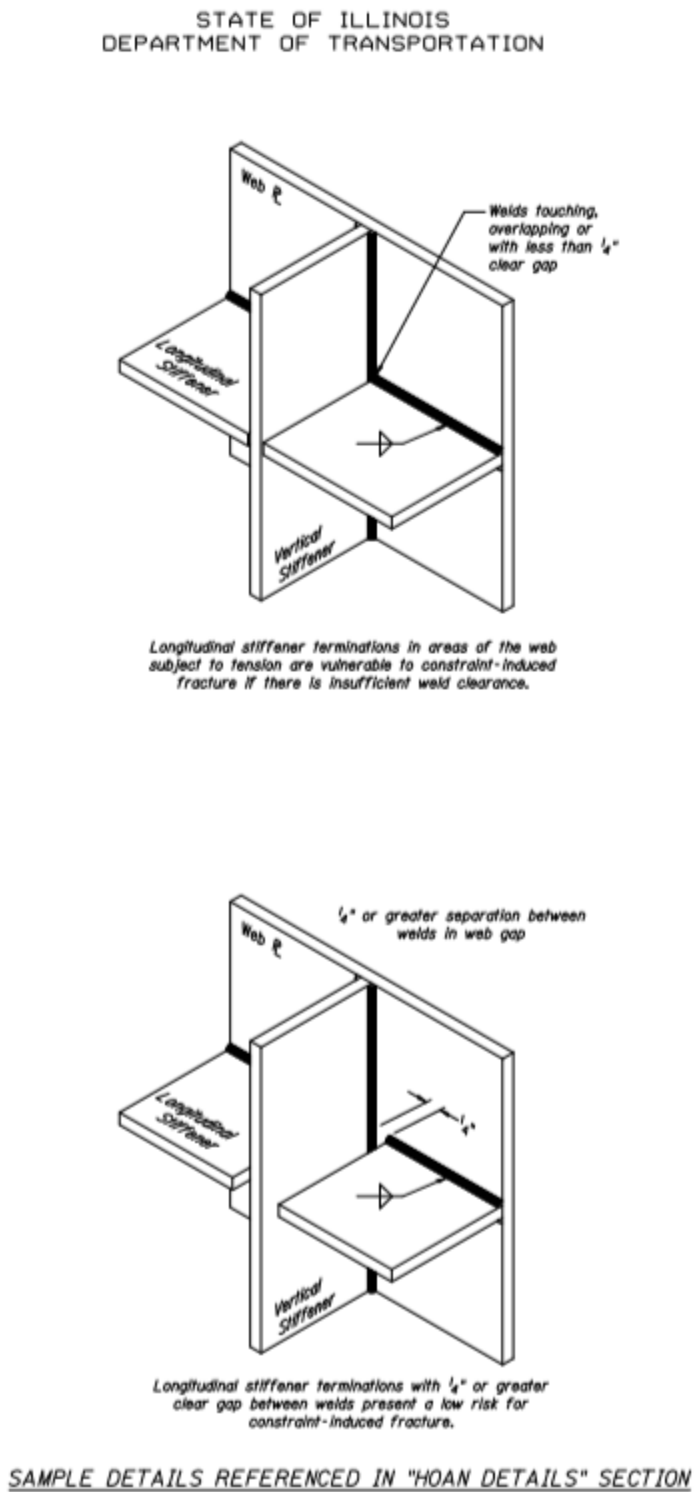

Figure 6 Constraint-induced fracture details from Illinois DOT Circular Letter 2010-09 (Attachment 4).

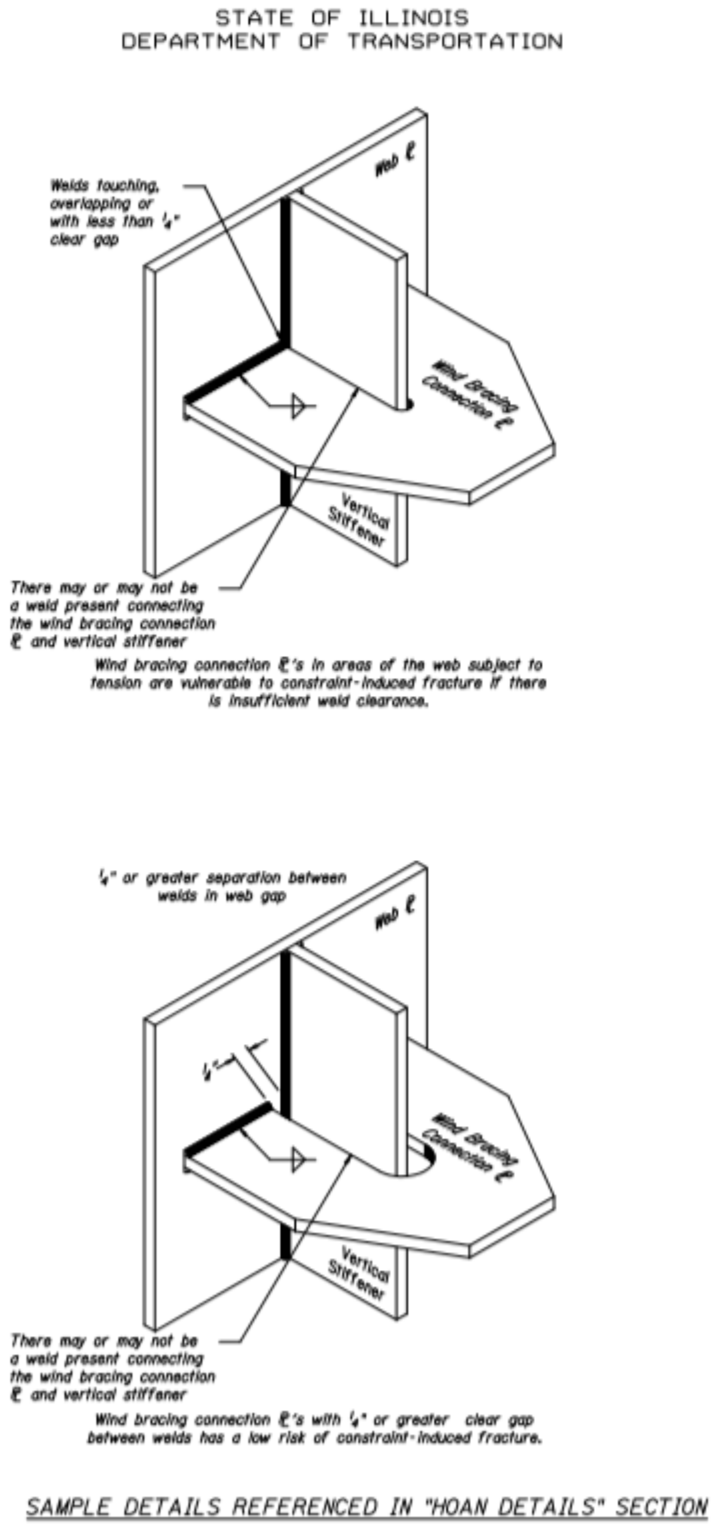

Figure 7 Constraint-induced fracture details from Illinois DOT Circular Letter 2010-09 (Attachment 5).

Figure 8 Fracture in interior girder of the northbound I-75 bridge over Lynn Camp Creek in Whitley County (2012).

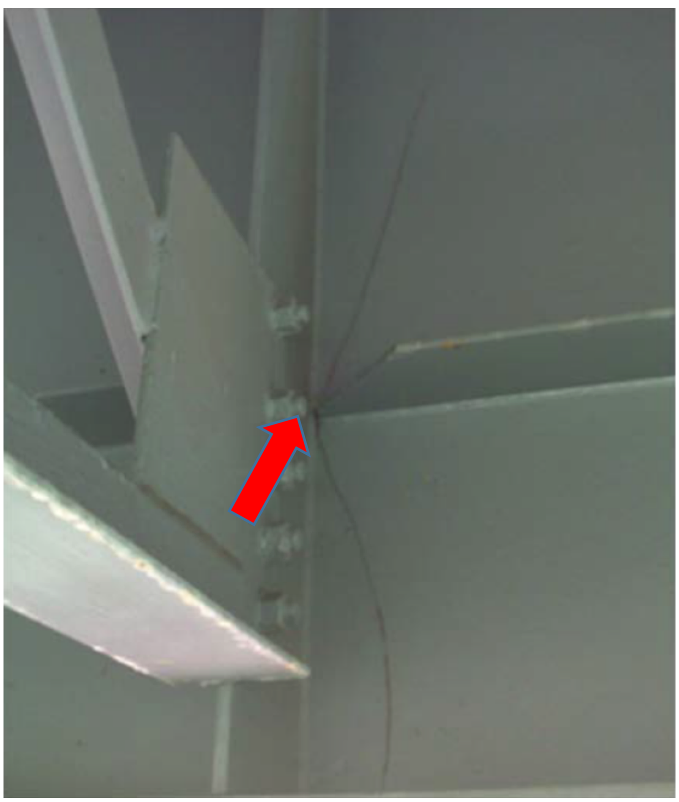

Figure 9 Fracture in interior girder of the southbound I-75 bridge over Lynn Camp Creek in Whitley County (2012). Note that the fillet welds attaching the horizontal and vertical stiffeners to the web appear to be in contact (arrow).

Figure 10 Fracture in interior girder of the northbound I-75 bridge over Lynn Camp Creek in Whitley County (2014).

Figure 11 Fatigue crack growth in the lower flange of the girder after the initial web fracture.

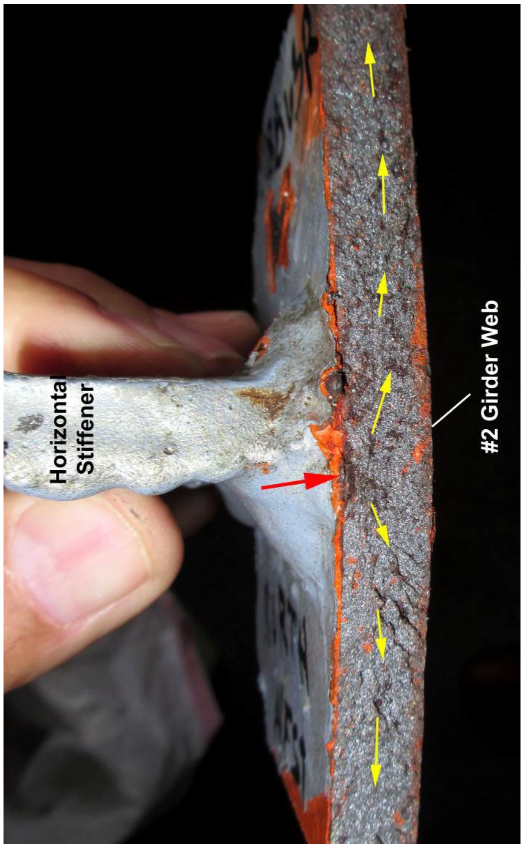

Figure 12 Fracture specimen showing web fracture surface and horizontal stiffener filler weld termination. Note the direction of the spreading unstable brittle fracture in the web (yellow arrows) and the fracture origin (red arrow).

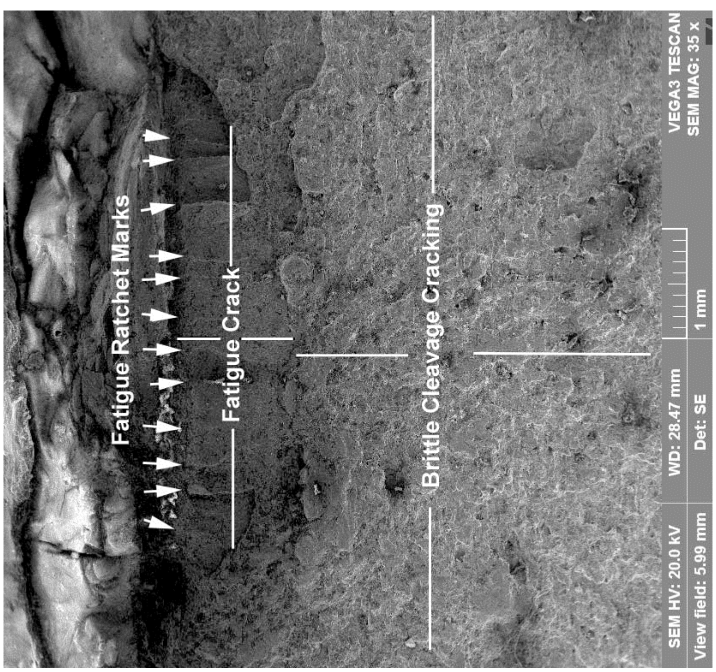

Figure 13 Scanning electron microscope image of the fracture surface in the area of the red arrow in Figure 12. Note the small (~ 5mm x 1mm) fatigue crack that precipitated the unstable brittle fracture of the girder web.

Figure 14 Bridge 045B00049N in Greenup County showing Hoan Detail which is typical throughout entire structure.

Figure 15 Bridge 073B00120R in McCracken County showing Hoan Detail which is typical throughout entire structure.

Figure 16 Bridge 040B00028R in Garrard County showing problematic CIF detail related to the gap between perpendicular fillet welds attaching gusset mounting bracket and vertical stiffener to web (arrow).

Figure 17 Check holes placed bracketing weld gaps on gusset in the I-794 Hoan Bridge.

Figure 18 Check holes that arrested CIF crack in gusset weld gap on the I-794 Hoan Bridge.