

From: [Nordholm, Gail \[DOT\]](#)
To: [Nordholm, Gail \[DOT\]](#)
Subject: Potential for Fracture to Occur in Iowa Steel Girder Bridges due to Triaxial Constraint
Date: Monday, January 24, 2011 3:16:00 PM

TO: County Engineers, City Representatives, and Consultants

CC: District Local Systems Engineers; Service Bureau; Bruce Brakke, Office of Bridges and Structures; and Office of Local Systems

FROM: Office of Local Systems

SUBJECT: Potential for Fracture to Occur in Iowa Steel Girder Bridges due to Triaxial Constraint

DATE: January 24, 2011

The following is being sent on behalf of the Office of Bridges and Structures. If you have any questions, **please do not reply to this note**. Instead, you may contact **Mike Todsén** as shown below.

* * * * *

There is potential for brittle fracture to occur at certain details on Iowa welded steel girder bridges, specifically at details which involve triaxial constraint. Triaxial constraint occurs when multi-directional welds intersect or come in close contact.

Crack extension by brittle fracture is different than cracks caused by fatigue. The cracks “pop” into the structure and crack growth occurs instantly in an unstable, dynamic fashion. In some cases, brittle fractures arrest in the structure, in other cases they result in full fracture of a structural member. There is no evidence of cracking prior to fracture initiation; therefore, even the most rigorous inspection will not provide warning of the impending fracture.

Fatigue cracks initiate from microscope flaws and slowly grow larger under the effects of live load. These cracks generally are found during periodic inspections and addressed before they become a serious problem.

It is not clear what triggers a brittle, “pop-in” fracture at a specific detail involving triaxial constraint. It likely occurs in the presence of a small flaw during low temperatures, in combination with a significant load event. Whether or not the fracture is arrested mainly depends upon the toughness of the steel.

The triaxial constraint problem is discussed in a August 19, 2010 Iowa DOT white paper entitled, “Potential For Fracture To Occur In Iowa DOT Steel Girder Bridges Due to Triaxial Constraint” (link below). In view of what has recently been learned, the potential for brittle fracture in 57 two girder bridges are being addressed as follows:

The girder web plate at the top of the pier bearing stiffeners is being inspected to determine if the stiffener to web welds intersect the web to flange welds or if the gap between the toes of the welds is less than 1/4 inch. If this condition is found, 2 in. or 3 in. diameter holes are cored through the web on both sides of the stiffeners. The core hole penetrates the horizontal and vertical fillet welds by approximately 1/8 inch.

A sketch of the retrofit is shown on Attachment 8 of the white paper.

http://www.iowadot.gov/local_systems/mailling/2011/january/potential_fracture.pdf

It is likely that triaxial constraint at the top of bearing stiffeners exists in some of our multi-girder bridges. However, these structures are not being retrofitted due to their redundancy and the rarity of brittle fractures.

There are some two girder bridges owned by the counties/cities that are similar to those owned by the Iowa DOT. A photo of a Iowa DOT bridge is attached. Typically, the two girder bridge is a three span structure, thus the potential of bearing stiffener retrofit exists at only two piers. A photo of the retrofit is at the link below:

http://www.iowadot.gov/local_systems/mailling/2011/january/triaxial_constraint_photos.pdf

This e-mail should be provided to the local entities. If there are questions regarding the retrofit, these can be directed to the Bridge Maintenance and Inspection Unit in the Office of Bridges and Structures.

If you have any questions regarding the retrofit, please contact Mike Todsén, P.E., Bridge Maintenance and inspection Unit, phone number 515-233-7726.

Thank you,

Bruce Brakke, P.E.
Office of Bridges and Structures
Iowa Department of Transportation

Some of the documents referenced above are in Adobe Acrobat's Portable Document Format (PDF). If you do not have the Adobe Acrobat Reader software, you can download it free of charge at:

<http://www.adobe.com/products/acrobat/readstep.html>.

Mailings are available at the Office of Local Systems Weekly Mailings web page at:

http://www.iowadot.gov/local_systems/mailing/main_mailing.htm

Potential For Fracture To Occur In Iowa DOT Steel Girder Bridges Due to Triaxial Constraint

Introduction

The purpose of this white paper is to provide information regarding the potential for fractures to occur at certain details on Iowa DOT welded steel girder bridges, specifically at details which involve triaxial constraint. Triaxial constraint occurs when multi-directional welds intersect or come in close contact.

There have been 34 fractures in Iowa steel bridges since the mid-1960s. At the time these occurred, none were identified as due to triaxial constraint. As explained herein, it is likely that 9 of the fractures occurred due to triaxial constraint.

There also have been many cracks in the web plates of Iowa welded girder bridges due to out-of-plane bending at diaphragm and floor beam connections, but none of these have resulted in fractures.

The locations of the 34 fractures are summarized below:

- a) Top of pier bearing stiffeners (5) --- Two shown in Attachments 1 & 2
 - b) Plug welded hole (5)
 - c) Plate welded to edge of girder flange (4)
 - d) Gusset plate connections for horizontal X lateral bracing (3) --- Two shown in Attachments 3 & 4
 - e) Flange to web weld (3) --- One shown in Attachment 5
 - f) Butt weld in cover plate (4)
 - g) Blast plate* welded to bottom flange (2)
 - h) Tie girder of tied arch(2)
 - i) Gouge in flange hit by high load (2)
 - j) End of cover plate (1) --- Shown in Attachment 6
 - k) Top of floor beam connection plate (1) --- Show in Attachment 7
 - l) Indentation in edge of flange (1)
 - m) Longitudinal weld in a truss chord member (1)
- * Plate attached to girders above railroad tracks

Triaxial Constraint

High levels of triaxial constraint contributed to major fractures in a I-794 bridge in Milwaukee, WI, in December 2000. The fractures were discovered in all three girders supporting the northbound roadway of I-794 over the Milwaukee River leaving the span near collapse. The structure is commonly known as the Hoan Bridge. Two girders were fractured full depth and the web of the third girder had several 3 ft. long fractures. All three girder fractures initiated at a gusset plate connecting K (chevron) lateral bracing to the girder web.

In February 2001, the FHWA recommended the state DOTs assess their bridge inventories to determine the number of structures that existed with similar details as the Hoan Bridge. After some discussion with the Iowa Division Office regarding what type of details should be reported, FHWA requested bridges with the following:

- K bracing in horizontal plane
- 2 or 3 girder bridges
- Gusset plate attached or not attached to the vertical connection plate
- Gusset plate close to bottom flange but not attached to it.

We advised FHWA that the Iowa DOT did not have any bridges with such details.

In July 2001, the FHWA provided information regarding the Hoan Bridge fractures. **The forensic investigation determined that the Hoan Bridge fractures were unique in that there was no evidence of fatigue prior to fracture.** The Summary Conclusion of the Forensic Investigation contained the following:

- “There was no evidence of fatigue cracking prior to fracture initiation. This indicates that there was no observable damage prior to the sudden fracture. Even the most rigorous fracture critical inspection would not have provided warning of the impending fracture.”
- “The fracture mode was positively identified as brittle, cleavage fracture. The fracture occurred suddenly and propagated through the girders at an explosive rate.”
- “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 occurring in this region. As a result, the local stress state in the web gap was forced well beyond the yield strength of the material. 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 April 2009, the Iowa DOT inspectors found a 3.5” fracture in the web of an exterior girder in the westbound I-80 bridge over the Cedar River. It appeared to have initiated at the top of the pier bearing stiffeners and extended down at about a 45 degree angle. In 1981, a 20” long fracture was found in a similar location on the eastbound bridge. These are two of the five fractures listed in (a) of the summary of the 34 fractures. There was no investigation of 1981

fracture or of the three fractures that occurred **at the top of bearing stiffeners** in other bridges in 1981 and 1982.

The westbound I-80 bridge was taken out of service in July 2009, as part of a replacement project for both twin bridges. This provided the opportunity to try to determine the cause of fracture. Wiss, Janney, Elstner (WJE) and Dr. Terry Wipf, Bridge Engineering Center, were retained to conduct the investigation. After the structure was closed, it was instrumented/load tested and material samples were obtained for Charpy V-notch toughness tests and fractographic evaluation.

WJE retained Drs. John W. Fisher and Eric Kaufmann to conduct the laboratory evaluation of the removed specimens. Both individuals were involved in the forensic investigation of the Hoan Bridge fractures.

The instrumentation and load testing is covered by the Bridge Engineering Center's report dated February 8, 2010. The load tests showed that the web gap fatigue stress range levels at the top of the pier bearing stiffener were relatively low. The instrumentation also showed the neutral axis at the pier was about six inches below the top flange, which results in low, in-plane, live load stress in the area of the fracture.

Drs. Fisher and Kaufman presented their laboratory findings in a March 31, 2010 letter report to WJE. They concluded:

“The fracture of the girder web was found to be initiated from the severe geometric triaxial restraint between the ends of the bearing stiffeners and the web-flange fillet welds. As a result the stress approached the web tensile strength. No evidence of fatigue crack growth was detected at the initiation site or at the arrested crack tip. The low levels of recorded stress range from tests (see Load Test to Assess Fatigue Detail Performance on the Westbound I-80 Bridge over the Cedar River, Bridge Engineering Center, February 8, 2010) also verified that fatigue crack development was not probable as the stress range cycles were below the fatigue limit”.

As mentioned earlier, the Hoan Bridge fracture involved a severe triaxial constraint condition due to intersecting welds. The investigators also believed the specific details of the lateral bracing connection resulted in a crack-like geometric condition which contributed to the fracture. They also believed that the K-type lateral bracing induced high forces in the short gap region. The I-80/Cedar River Bridge investigation indicates that **triaxial constraint alone can result in brittle fracture**.

Based on the I-80/Cedar River Bridge investigation, I believe it is likely that the five fractures at the “top of pier bearing stiffeners” and the one at the “top of floorbeam connection plate” were caused by triaxial constraint. The three fractures at the “gusset plate connection for X horizontal lateral bracing” were probably also caused by this condition. These are items a), k) and d), respectively, on Page 1.

Based on what is being learned, welded details with intersecting welds or narrow gaps result in triaxial constraint. This condition exists in numerous bridges. Fortunately, the occurrence of fractures due to this condition is rare; however, some fractures caused by triaxial constraint probably have not been identified as such. Examples would be the nine mentioned in the paragraph above. One of the fractures at the gusset plates severed the bottom flange/web and entered the top flange. The other two were up to 32” long in the web and one entered the bottom flange.

One of the five fractures at the “top of pier bearing stiffeners” severed the top flange and the entire web, another ran about 20” down the web and the remaining three were less than 6” long. One of the three was in a two girder bridge.

During preparation of this paper, I became aware of the 2007 article in the ASCE Journal of Bridge Engineering entitled, “Preventive and Mitigation Strategies to Address Recent Brittle Fractures in Steel Bridges”. **It does not address triaxial constraint at the top of pier bearing stiffeners and the potential for fractures at such locations.**

The article covers two case studies, the US422 Bridge over the Schuylkill River in Pennsylvania and the Hoan Bridge. The US422 Bridge had a brittle fracture due to triaxial constraint at a lateral gusset plate connection to the girder web. I believe it is likely that this fracture is basically the same as the three listed in d) on Page 1.

Observations Regarding Flange to Web Welds and Intersecting Welds

Flange to Web Welds

Some of the plans for Iowa DOT bridges designed in about 1959 specified the girders be fabricated with a full penetration web to flange weld, if the web plate was thicker than 3/8 inch. If the plate was 3/8 inch or thinner, fillet welds were specified. In subsequent years, fillet welds on each side of the web plate were used for this connection.

The plans for four of the fractured girders listed in (a) on Page 1 specified that they be fabricated with the full penetration web to flange weld. The plans for the other bridge specified fillet welds. The investigation of the fractured girder on the I-80 bridge over the Cedar River confirmed that a full penetration weld was used. It is not known if full penetration welds were actually used on the other three fractured girders.

During the investigation of the I-80/Cedar River fracture, Dr. Fisher was asked if the unusual requirement for a full penetration web to flange weld made this condition more susceptible to fracture. His response was:

“I think the full penetration requirement was a contributing factor. It would result in much more plastic strain demand on the thin web plate from weld shrinkage. With the triaxial restraint this would help push you further along the path to the material’s tensile strength.”

The plans for two of the three fractured girders listed in (e) specified a full penetration web to flange weld. Two of the fractures were investigated. One had a full penetration weld and the other had fillet welds. The report for the girder with the full penetration weld had the following statement:

“The final failure mode was observed to be by classic brittle, cleavage fracture. There is clear evidence of the typical chevron pattern that points back to the initiation site of the fracture. A weld defect was identified as the initiation site of the brittle fracture. There was no evidence of fatigue crack inclination or growth prior to fracture.”

“Under a 60 power microscope, the defect appeared to be some type of inclusion. The appearance was hard and glossy, suggesting a slag inclusion in the weld. This very small defect could be identified as the initiation site of the brittle fracture. The chevron lines point to the top left corner of the defect as the actual initiation point. The defect measured about 3/16 inch by 9/16 inch.”

Intersecting Welds

The 1959 plans for three of the eight bridges listed in (a) and (e) had the following note:

“Do not intersect stiffener weld with longitudinal web weld (typical).”

In the 1980s, Standard Sheet 1021 was issued to address the termination of welds, specifically the ends of fillets that connect bearing stiffeners, diaphragm connection plates and vertical stiffeners to girder webs. The distance between the end of those welds and web to flange weld was set at 5 times the web thickness with a minimum of 2 ¼ inches.

Conclusion

Brittle fracture in bridges is a safety concern. The following discussion is from the Hoan Bridge investigation.

“Most cracks found during inspection of structures are caused by fatigue. Under normal conditions, fatigue cracks initiate from microscopic flaws and slowly grow larger under the effects of live load. The rate of growth is proportional to the stress range and frequency of loading on the structure. Geometry also has an effect on crack growth rate. Cracks located near details that cause stress concentration grow faster than those out in undisturbed areas of a steel plate. These conditions vary between structures and it is difficult to estimate a generic crack growth rate for all cases. However, the conditions present in bridge structures almost always result in slow, stable crack growth rates.”

“Crack extension by brittle fracture is different. The cracks immediately “pop” into the structure and crack growth occurs instantly in an unstable, dynamic fashion. In some cases, brittle fractures arrest in the structure, in other cases they result in full fracture of a structural member. In cases where crack arrest occurs, the resulting crack cannot be distinguished from a fatigue crack based on visual inspection of the surface of the structure. In some cases, an arrested fracture will become a fatigue crack and continue to slowly extend in a stable manner.”

“Brittle fractures occurring any place in a structure are a very serious safety concern. These can cause immediate loss of part or all of the capacity of the structure and in the worst case will cause collapse. The Hoan Bridge is a rare example of the worst case scenario.”

It is not clear what triggers a brittle, “pop-in” fracture at a specific detail. It likely occurs in the presence of a small flaw during low temperatures, in combination with a significant load event. Whether or not the fracture is arrested mainly depends upon the toughness of the steel.

In view of what has recently been learned, the potential for brittle fracture on Iowa DOT two girder bridges should be addressed as follows:

The girder web plate at the top of the pier bearing stiffeners should be inspected to determine if the stiffener to web welds intersect the web to flange welds or if the gap between the toes of the welds is less than ¼ in. If this condition is found, 2 in. or 3 in. diameter holes should be cored through the web on both sides of the stiffeners. The core hole would penetrate the horizontal and vertical fillet welds by approximately 1/8 inch. This retrofit is shown on Attachment 8.

Gusset plates for lateral bracing in tension areas should be inspected to determine if there are intersecting welds in the corner formed by the web, gusset plate and connection plate. If this condition exists (or if the gap between the toes of the welds is less than ¼ in.), a hole should be cored thru the gusset plate corner to increase the gap length. This retrofit is shown on Attachment 9.

The ¼ inch minimum gap between welds is based on research conducted subsequent to the Hoan Bridge fractures. The results of research is covered in an article in the Journal of Computer-Aided Civil and Infrastructure Engineering entitled, "Finite Element Investigation of the Fracture Potential of Highly Constrained Details" and in the previously mentioned ASCE article, "Preventive and Mitigation Strategies to Address Recent Brittle Fractures in Steel Bridges".

It is likely that triaxial constraint at the top of bearing stiffeners exists in many multi-girder bridges. However, it is not recommended that these structures be retrofitted due to their redundancy and the rarity of brittle fractures.

Implementation

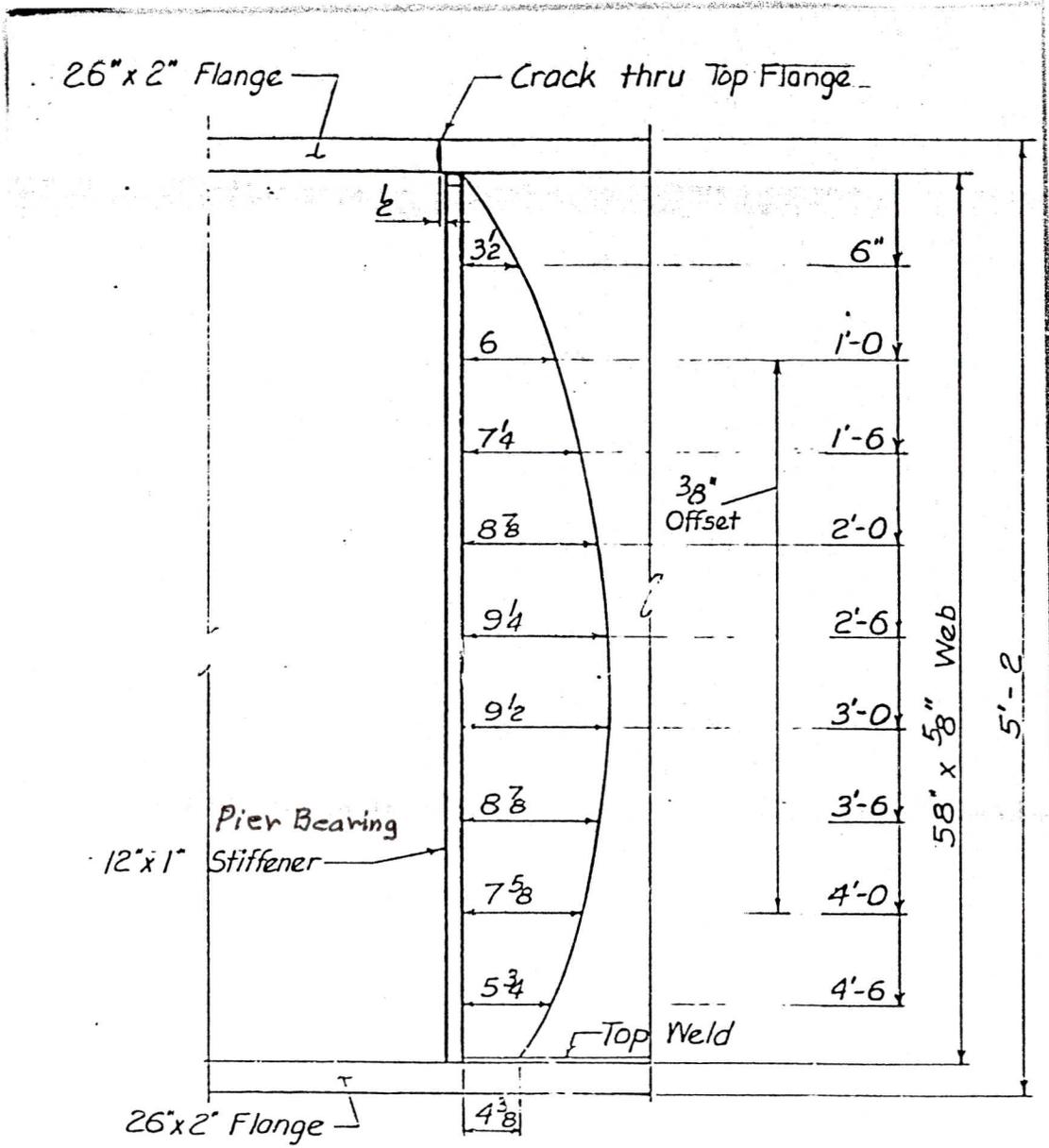
There are 57 two girder bridges that should be evaluated for triaxial constraint. One is the "Mile Long Bridge" over the Red Rock Reservoir on Iowa 14. One of the fractures listed in Item a) on Page 1 is at Pier 41 of this structure. Wiss, Janney, Elstner (WJE) is being retained, under the statewide on-call agreement with the firm, to remove plug welded holes in the bottom flange of eleven of the floorbeams. The firm should also be retained to core holes in the web on each side of the pier bearing stiffeners, where needed. This retrofit will stop any unstable crack extension or fracture out of the short gap region.

One of the staff engineers in the Bridge Maintenance and Inspection Unit (BMI) and, desirably, each of the six District Bridge Repair Specialists (DBRSs) would be at the bridge to observe WJE coring several holes at the bearing stiffeners. Subsequently they could then perform the retrofit on the other two girder bridges, where needed. However, if the DBRSs do not have the time to perform the retrofits, WJE should be retained to perform the work.

Most of the 57 two girder bridges are three span structures, thus the potential for bearing stiffener retrofit exists at only two piers. Very few of the two girder bridges have lateral bracing in tension areas so the number of gusset plates that need to be retrofitted should be small.

There are a few similar two girder bridges owned by the counties/cities. The triaxial constraint problem should be discussed with those entities.

Prepared by: Bruce Brakke, P.E.
Bridge Maintenance Engineer
Iowa DOT
August 19, 2010



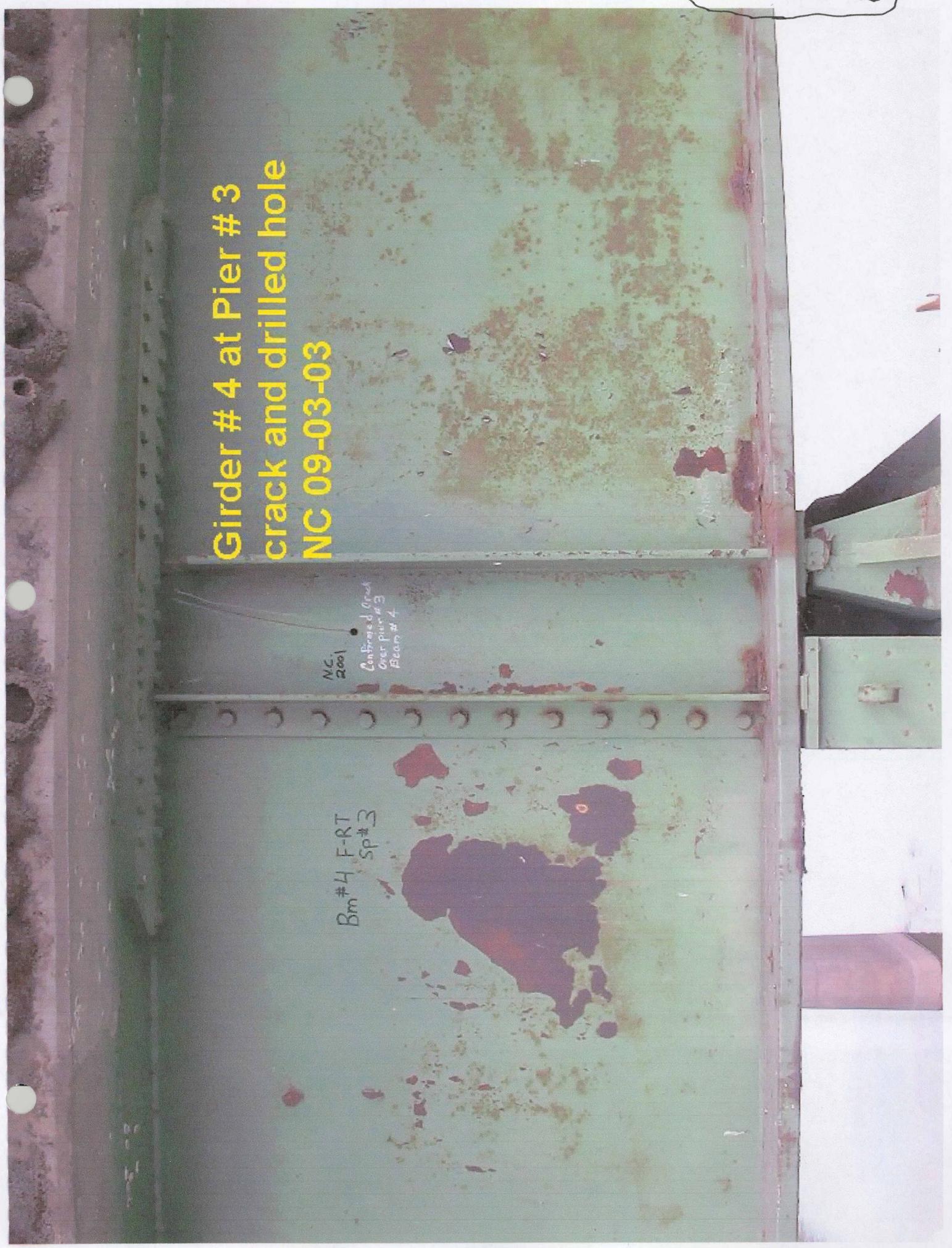
Partial View - South Interior Girder - Looking South
West Bound Bridge - Pier #5

Scale 1/2" = 1'-0"

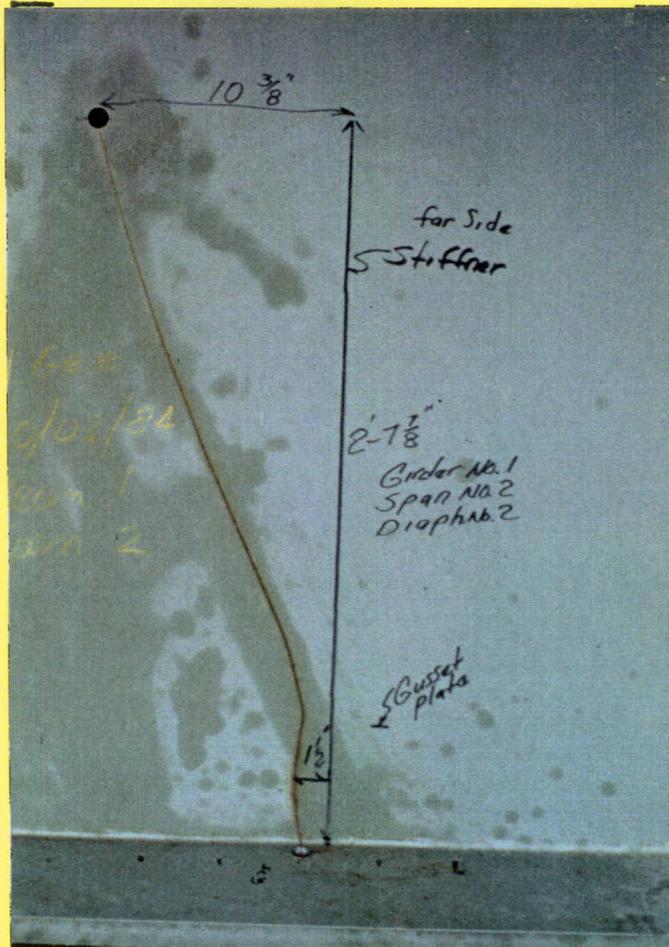
Girder # 4 at Pier # 3
crack and drilled hole
NC 09-03-03

NC
2601
Confined Area
Over Pier # 3
Beam # 4

Bm #4 F-RT
Sp #3



Attachment 3
1 of 2



SLIDE NO. 17

DESCRIPTION

Span #2, Girder
#1, Diaphragm
#2, (LEFT Side

DATE 10/23/84

SLIDE NO.

DESCRIPTION

DATE

SLIDE NO. 18

DESCRIPTION

Span #2, Girder
#1, Diaphragm
#2 (Right Side

DATE 10/23/84

SLIDE NO. 19

DESCRIPTION

Span #2, Girder
#1, Diaphragm
#2 (Right
Side)

DATE 10/23/84

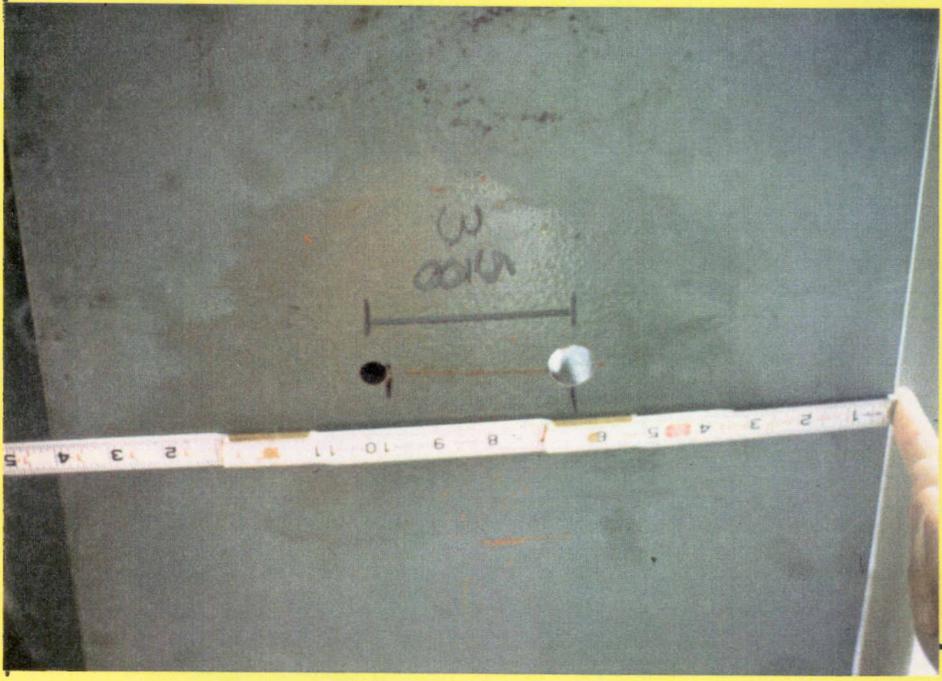


SLIDE NO. 20

DESCRIPTION

Span #2, Girder
#1, Diaphragm #2,
Bottom Flange,
Bottom View

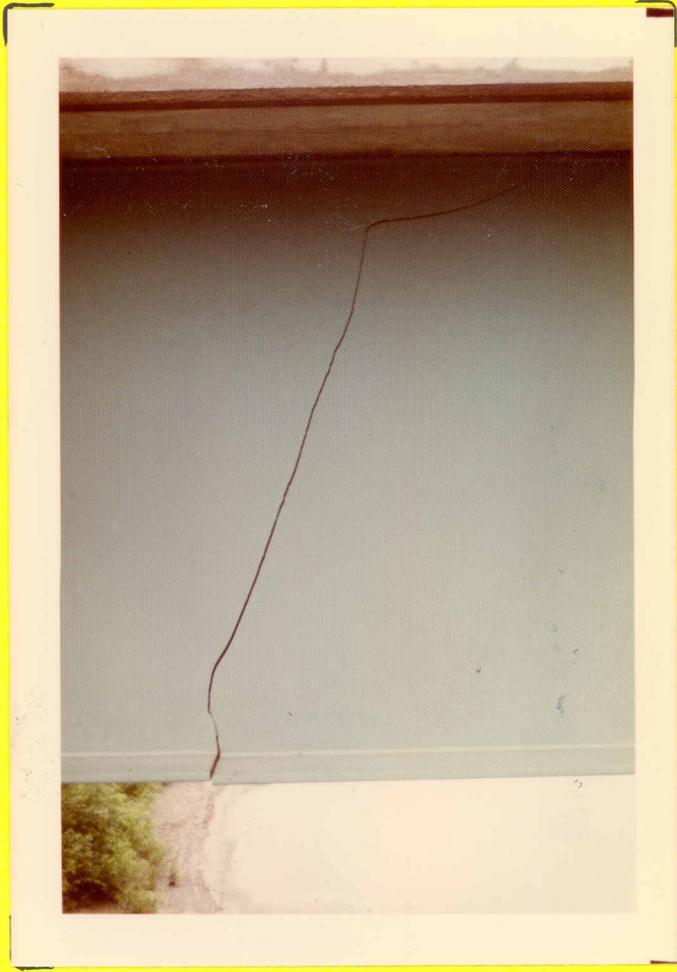
DATE 10/23/84



SLIDE NO.

DESCRIPTION

DATE _____

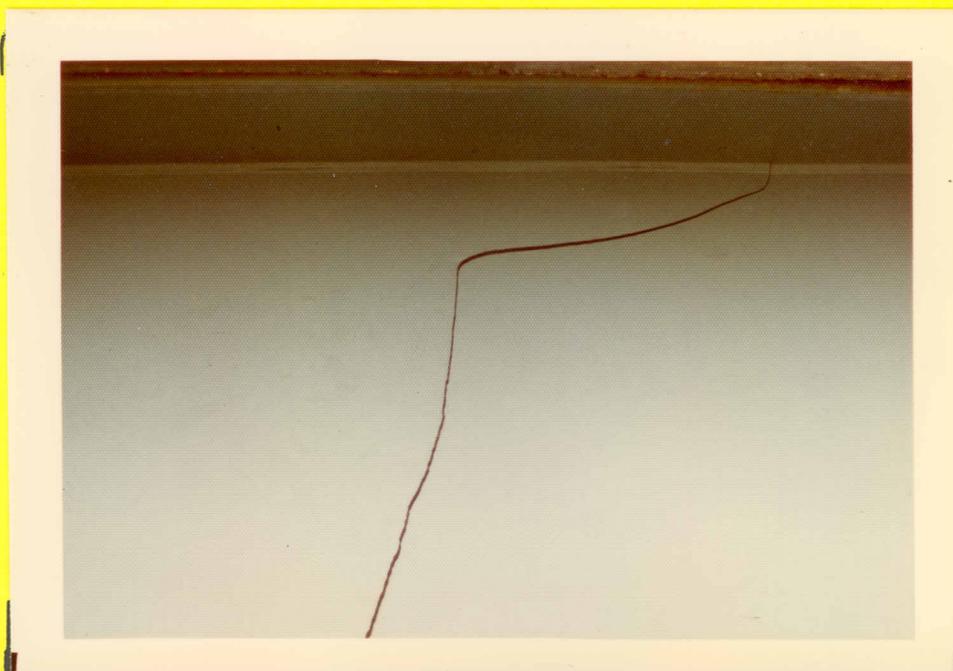


SLIDE NO. 251

DESCRIPTION

Exterior Face

DATE 8-1-79



SLIDE NO. 252

DESCRIPTION

Exterior Face

DATE 8-1-79

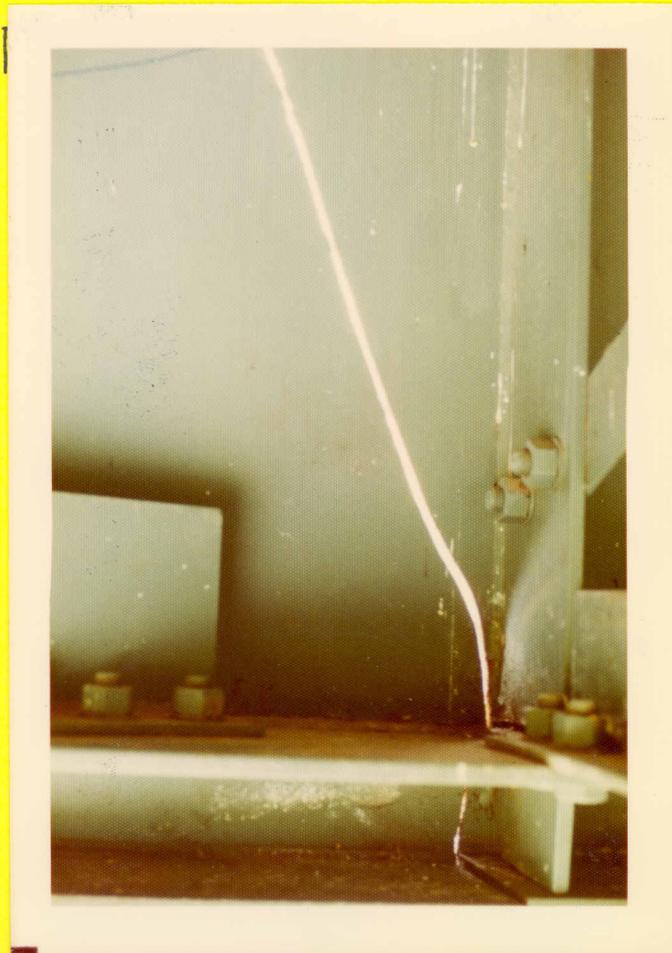


SLIDE NO. 261

DESCRIPTION

Weld-gusset
to web stiffener

DATE 8-1-79



SLIDE NO. 262

DESCRIPTION

Top of gusset
Plate

DATE 8-1-79



Figure 1

Full depth crack in the exterior girder of the Cherokee County Bridge.

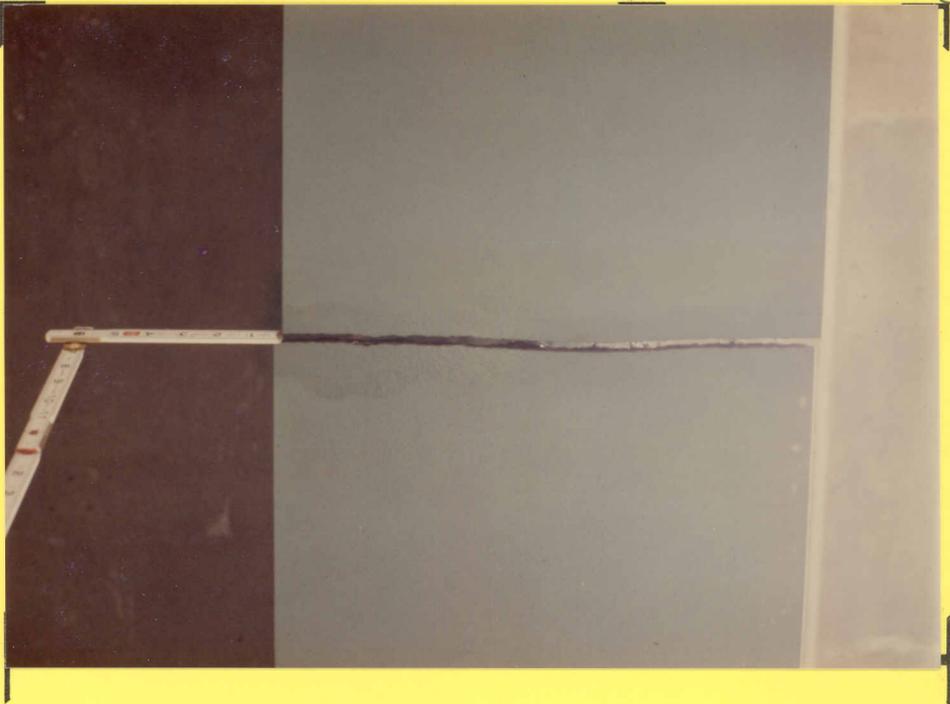
Investigation determined fracture initiated at web to flange weld. No evidence of fatigue crack initiation or growth prior to fracture.

Slide No. 3

DESCRIPTION

Bottom flange
Down to Up

Date 4-88



Slide No. _____

DESCRIPTION

Date _____

Slide No. 4

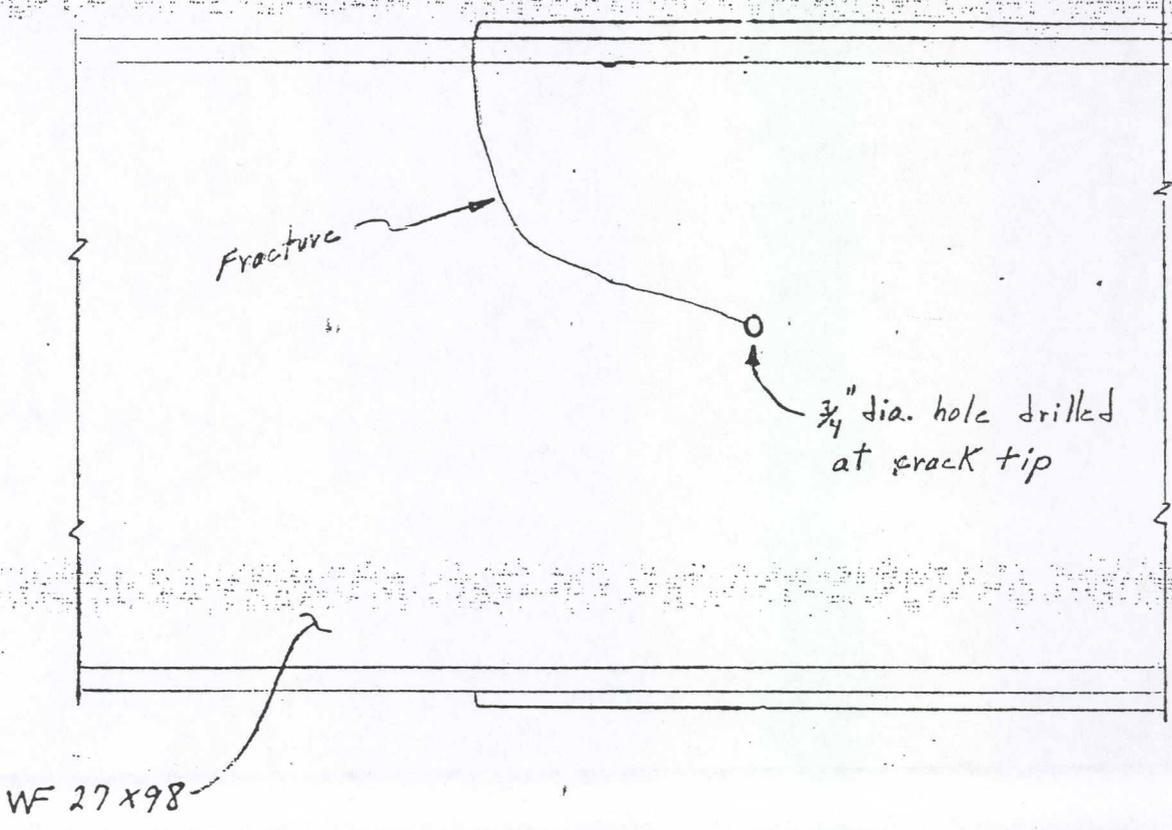
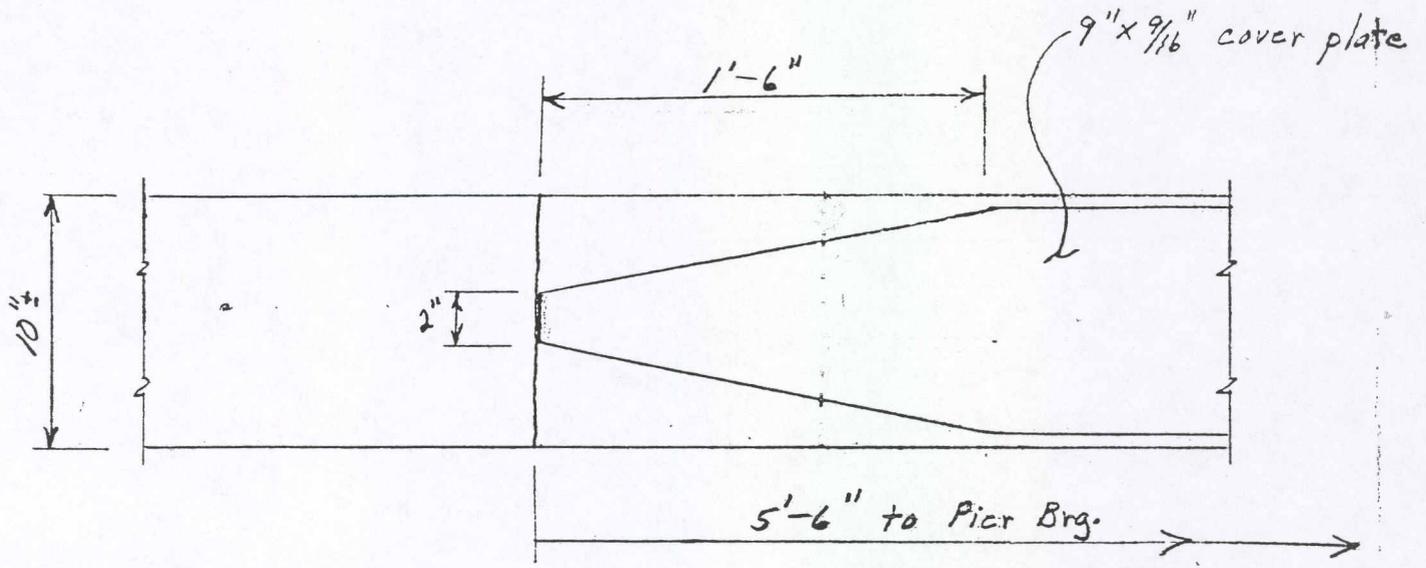
DESCRIPTION

Right Bottom
Flange
(FAR-NEAR)

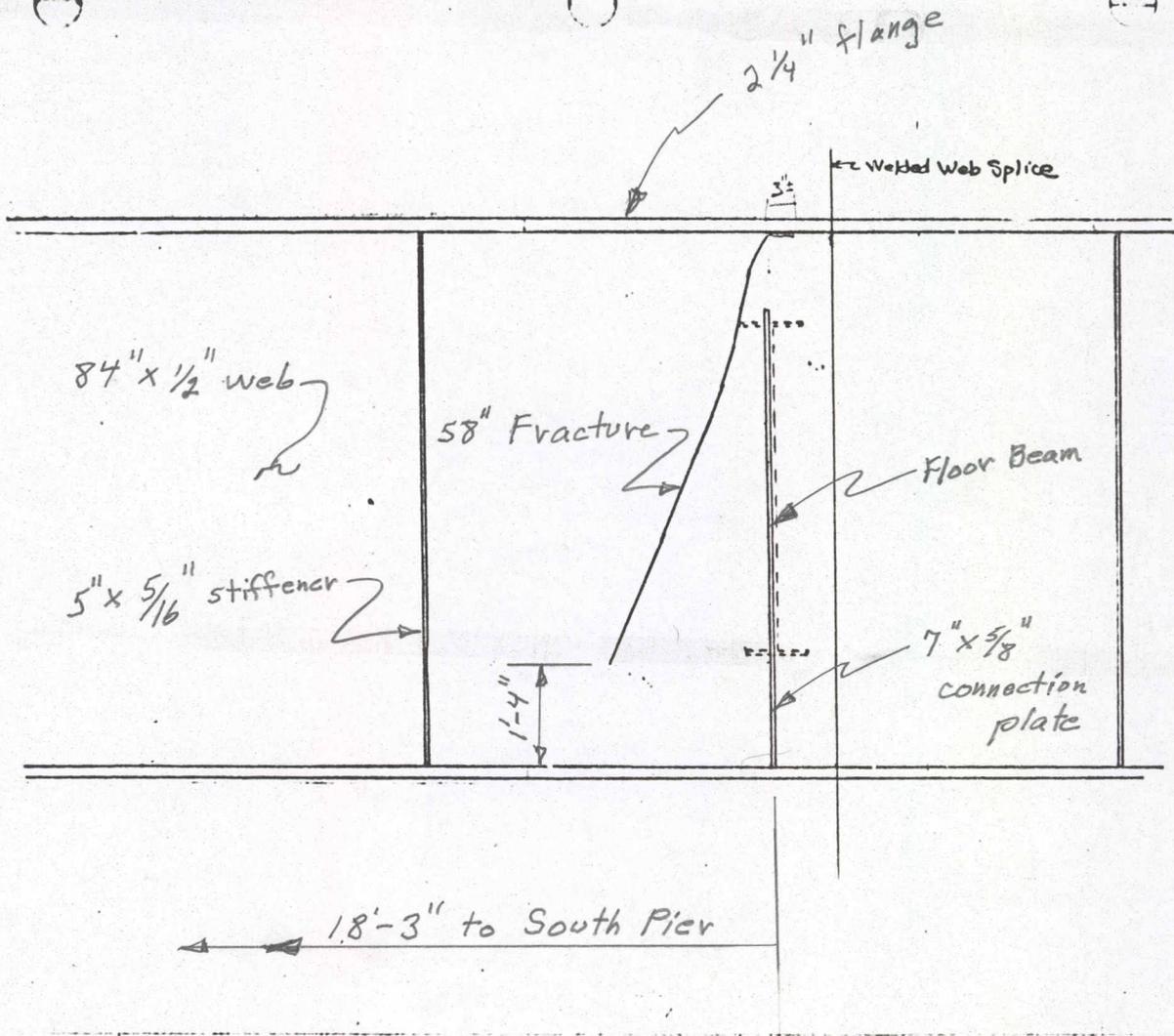
Date 4-88



Attachment 6

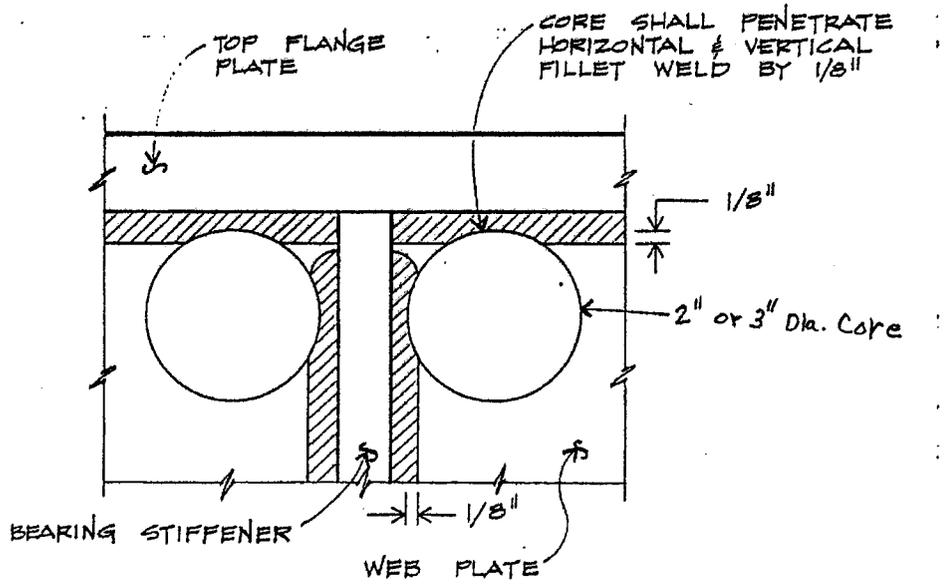


Attachment 7

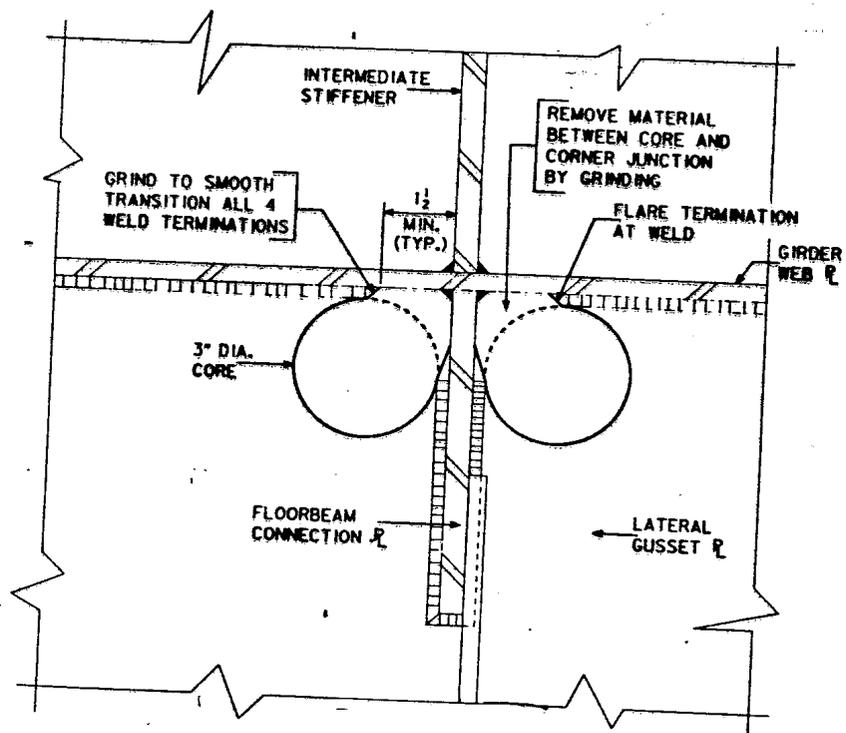


Two Girder Bridge (130'-166'-130')

5325.95151



Pier Retrofit Detail



LATERAL GUSSET PLATE RETROFIT DETAIL



