

***A-588 BRIDGE MOUNTED SIGN
FAILURE INVESTIGATION***

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Michigan Department of Transportation

CONSTRUCTION AND TECHNOLOGY DIVISION

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16. Abstract This report documents the results of a failure investigation of a weathering steel (ASTM A-588) sign support that was attached to an unpainted weathering steel bridge beam. The sign had a bolted connection detailed according to Michigan Department of Transportation (MDOT) Sign Standard Plan VIII-820E. This detail uses a W-section steel beam that is bolted to, and cantilevers from, the web of a steel bridge fascia beam. The cause of the failure was pack rust in the interface between the sign support's steel angles and the beam web. The pack rust introduced large tension (prying) forces in the bolted connection, and there was insufficient engagement of the nut's threads because the bolts used on the connection were too short. The investigation prompted a statewide inspection of MDOT's sign supports attached to weathering steel bridge beams. The inspection found other sign supports on weathering steel bridge beams with problems such as pack rust, missing bolts, fractured bolts, and short bolts. Recommendations are provided for inspection of sign supports on bridges and for modification of the MDOT sign standard detail.			
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**MICHIGAN DEPARTMENT OF TRANSPORTATION
MDOT**

A-588 BRIDGE MOUNTED SIGN FAILURE INVESTIGATION

DAVID JUNTUNEN, P.E.

**TESTING AND RESEARCH SECTION
CONSTRUCTION AND TECHNOLOGY DIVISION
RESEARCH PROJECT TI - 1976
RESEARCH REPORT R-1408**

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Lowell B. Jackson, Brian K. Larche
Gregory J. Rosine, Director
Lansing, January 2002**

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The author thanks Roger Till for useful comments and guidance during this investigation, Larry Pearson, Chris Davis, Steve Kahl, and Bryon Beck for dedicated work on this project including developing a data base, inspection of the bridges, lab testing, and assistance in producing this report. Michigan Department of Transportation's (MDOT's) seven Regions, and Construction and Technology's Bridge Operations Unit are thanked for their cooperation, expedited inspection, and prompt retrofit of sign supports on MDOT's A-588 bridges.

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EXECUTIVE SUMMARY

At the request of the Metro Region, the Structural Research Unit (SRU) investigated the cause of failure of a 10 ft by 6 ft bridge-mounted sign support. The overhead sign was attached to Structure Number S07 of 63191, which carries I-696 west bound over M-102. The incident happened on June 11, 2001. The sign was supported from the bridge using a bolted connection detailed according to Sign Standard Plan VIII-820E. This detail uses a W-section steel beam that is bolted to, and cantilevers from, the web of a steel bridge fascia beam.

The cause of the failure was pack rust in the interface between the sign support's steel angles and the beam web. The pack rust introduced large tension (prying) forces in the bolted connection, and there was insufficient engagement of the nut's threads because the bolts used on the connection were too short.

The investigation prompted a statewide inspection of MDOT's sign supports attached to A-588 (weathering steel) bridge beams. The expedited inspection prevented several overhead sign failures. Of the 25 bolted A-588 sign supports on MDOT bridges, 16 (64 percent) had problems including missing and fractured bolts, pack rust between the contact surface of the sign connection and the beam web, and short bolts. Fortunately, on MDOT's 528 A-588 bridges, there are only 31 A-588 sign supports (including welded connections). The A-588 sign supports were primarily on bridges built before 1974. Bridges built after that date, and sign connections that have been placed or replaced since that time are galvanized steel. However, four of 264 galvanized supports also had missing bolts or pack rust. The problems found on the galvanized steel sign supports were not nearly as severe as the problems found on the A-588 supports; however, bridge inspectors should be aware of the potential for pack rust to develop between galvanized sign support connections when they are attached to A-588 beams.

On painted steel bridge beams, pack rust should not occur since the bridge beam is coated with the Department's three coat paint system prior to the sign being attached to the structure, and the sign connection is galvanized. Recommendations are provided for inspection of sign supports on bridges and for modification of the sign standard detail to prevent pack rust from developing at the connection interface.

ACTION PLAN

1. Engineering Operations Committee
 - a. Approve Report R-1408, A-588 Bridge Mounted Sign Failure Investigation.
2. Construction and Technology, Bridge Operations Section
 - a. Provide an item within the Bridge Inspection Report for inspecting sign supports. This will provide a reminder to inspectors to inspect sign supports, and provide a consistent location on the Bridge Inspection Reports for documenting this information.
3. Regions
 - a. Replace all A-588 sign supports with galvanized steel sign supports. When replacing a sign support the connection interface (faying surface) should be blast cleaned, and primed with organic zinc-rich paint before placing the new connection. The paint shall overlap the perimeter of the connection by 2 inches. The paint color shall be "Brown Weathering Steel," Federal Code Number 10062. Bolts shall be long enough to extend beyond the top of the nut at least two thread pitches. The perimeter of the connection shall be sealed with an approved silicone sealant. High strength A-325 Type 3 bolts shall be used when attaching a support to A-588 steel.
 - b. Bridge inspectors should inspect sign supports on bridges for pack rust, missing bolts, short bolts (bolts where the bolt does not project completely through the nut), or impact damage. If pack rust or missing bolts are discovered, or if the sign support has structural damage, the Regional Maintenance Engineer should be notified, and a close inspection of the sign connection should be done to confirm if pack rust is present or bolts are missing or fractured. If any bolts are missing or fractured or if pack rust is discovered between the connection interface, all bolts on the support should be replaced and the perimeter of the connection should be sealed with an approved silicone sealant as soon as possible. Depending on the sign support's condition, it should be scheduled for replacement, or the support should be taken down, the connection interface (faying surface on the support angle and the beam web) should be blast cleaned, and primed with organic zinc-rich paint before re-erecting the support. If the beam is unpainted A-588 steel, the paint color shall be "Brown Weathering Steel," Federal Code Number 10062, and the paint shall overlap the perimeter of the connection by 2 inches, otherwise blend the paint to the existing paint. Bolts shall be long enough to extend beyond the top of the nut at least two thread pitches. The perimeter of the connection should be sealed with an approved silicone sealant. High strength A-325 Type 3 bolts should be used when attaching a support to A-588 steel.

4. Traffic and Safety Division

- a. Add the following notes to the Sign Standard Plans VIII-820E and VIII-830E:

When the sign support is attached to A-588 bridge beams the connection interface should be blast cleaned, and primed with organic zinc-rich paint before placing the new connection. The paint shall overlap the perimeter of the connection by 2 inches. The paint color shall be "Brown Weathering Steel," Federal Code Number 10062. The perimeter of the contact surface of the sign supports connection to the beam web shall be sealed in accordance to Subsection 713.03.F of the Standard Specifications.

The bolted connection of the sign support to the beam web shall be according to Subsection 707.03.D.9 of the Standard Specifications (Subsection 707.03.D.7 of the interim 2003 Standard Specifications).

- b. By strength analysis, the bolt design connecting the sign bracket to the beam web is satisfactory, however, adding two additional bolts to each angle would provide additional redundancy to the bolted connection. Figure 16 shows recommended changes to Sign Standard Plans VIII-820-E and VIII-830E. The redesign satisfies AASHTO, Standard Specifications for Highway Bridges Sixteenth Edition, 1996, Subsection 10.24.6.1, Sealing Against Moisture Penetration. The vertical leg of the angle is made longer to allow the bolt to be moved closer to the center of the connection without interfering with the W-section/angle weld.

INTRODUCTION

At the request of the Metro Region, the Structural Research Unit (SRU) investigated the cause of failure of a 10 ft. by 6 ft. bridge-mounted sign connection. The overhead sign was attached to Structure Number S07 of 63191, which carries I-696 west bound over M-102. The incident happened on June 11, 2001.

The sign was supported from the bridge using a bolted connection detailed according to Sign Standard Plan VIII-820E. This detail uses a W-section steel beam that is bolted to and cantilevers from the web of a steel bridge fascia beam. An example of this type of sign support is shown in Figure 1.

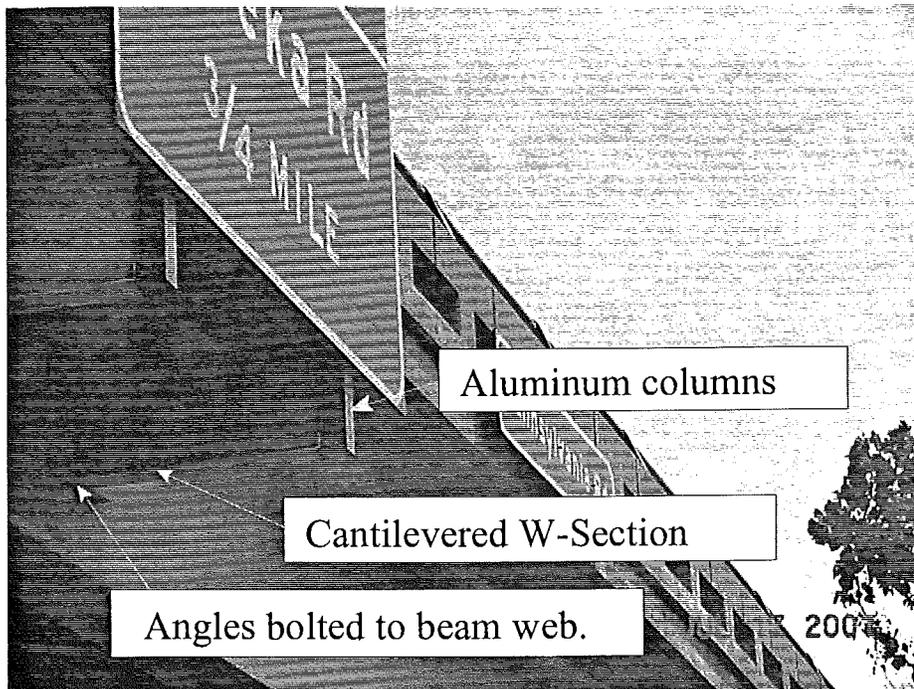


Figure 1 - Typical bolted sign connection, Type C or D.

FAILURE ANALYSIS

Our investigation of the failed sign connection revealed the following:

1. The bridge beams were manufactured from ASTM A-588 steel. A-588 steel is a high-strength low-alloy structural steel that is formulated to have better atmospheric corrosion resistance capabilities. Advocates of this steel claim that it does not need to be painted. The cantilevered sign support was also manufactured of A-588 steel. We found an extensive build-up of rust (approximately 0.225 inch thick) between the contact surfaces of the beam web and the sign connection's steel angles (see Figures 2 through 4).
2. All the bolts that we were able to recover were stripped, (see Figure 5), and the engagement length on the bolt thread was smaller than the depth of the connecting nut.

The pack rust in the interface between the steel angles and the beam web introduced large tension (prying) forces in the bolted connection. There was insufficient engagement of the nut's threads to the bolts connecting the beam web to the steel angles of the sign support. Without sufficient thread engagement length, a bolt cannot develop its full capacity. The pack rust induced tensile forces in the bolts great enough to strip the threads on the inadequately engaged nuts.

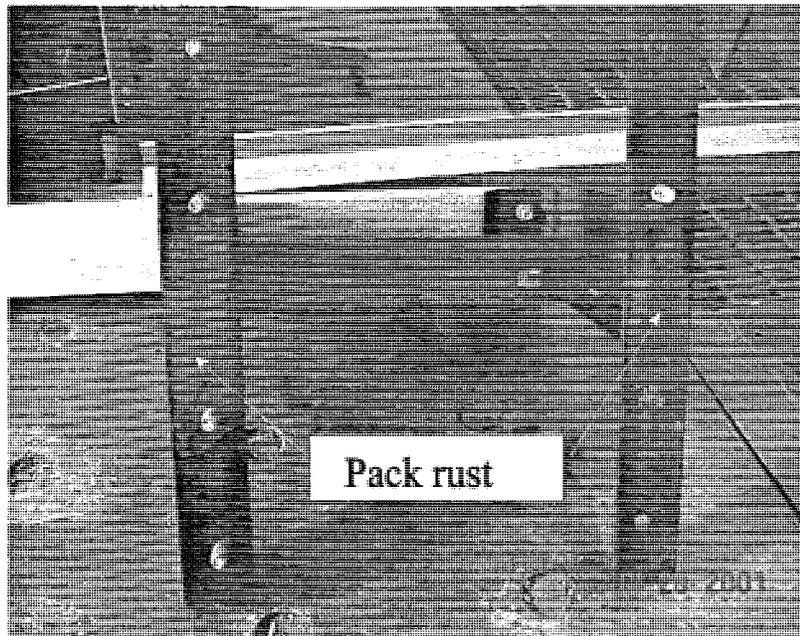


Figure 2 - Pack rust on the back side of the steel angles on sign connection that was attached to Structure Number S07 of 63191.

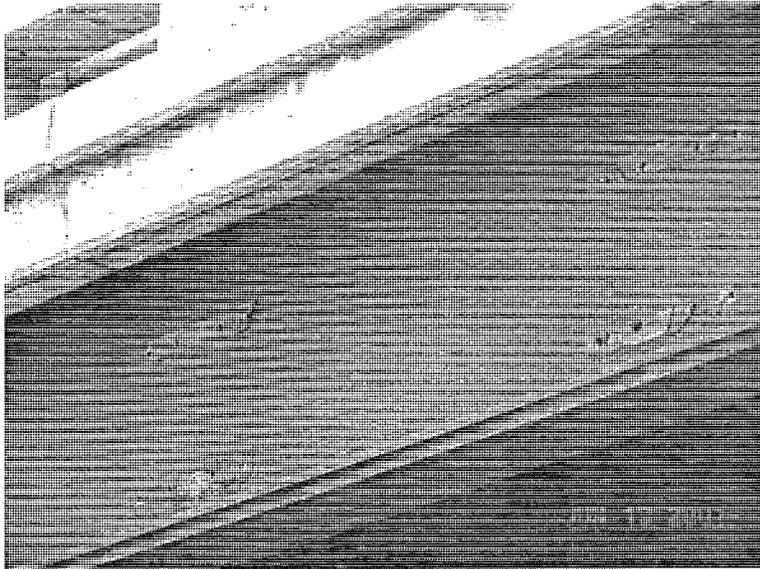


Figure 3 - Pack rust left on the beam web. Structure Number S07 of 63191.

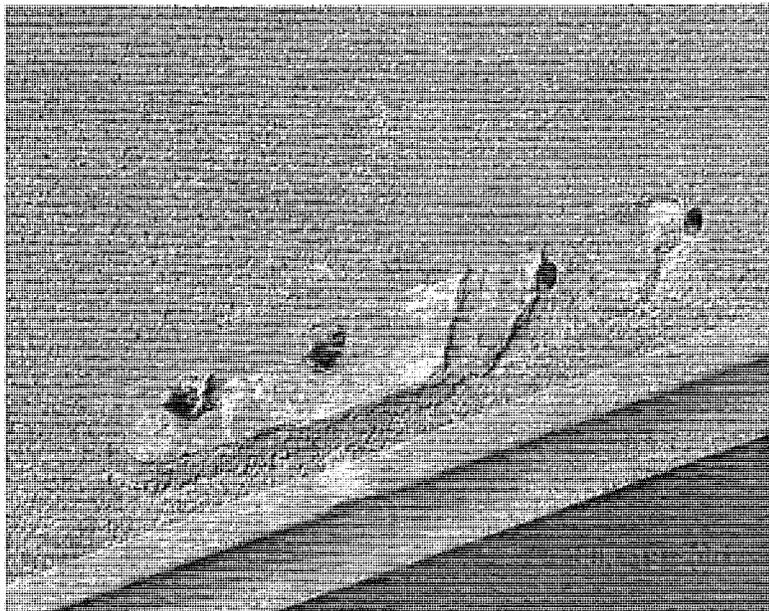


Figure 4 - Close-up of pack rust on beam web. Structure Number S07 of 63191.

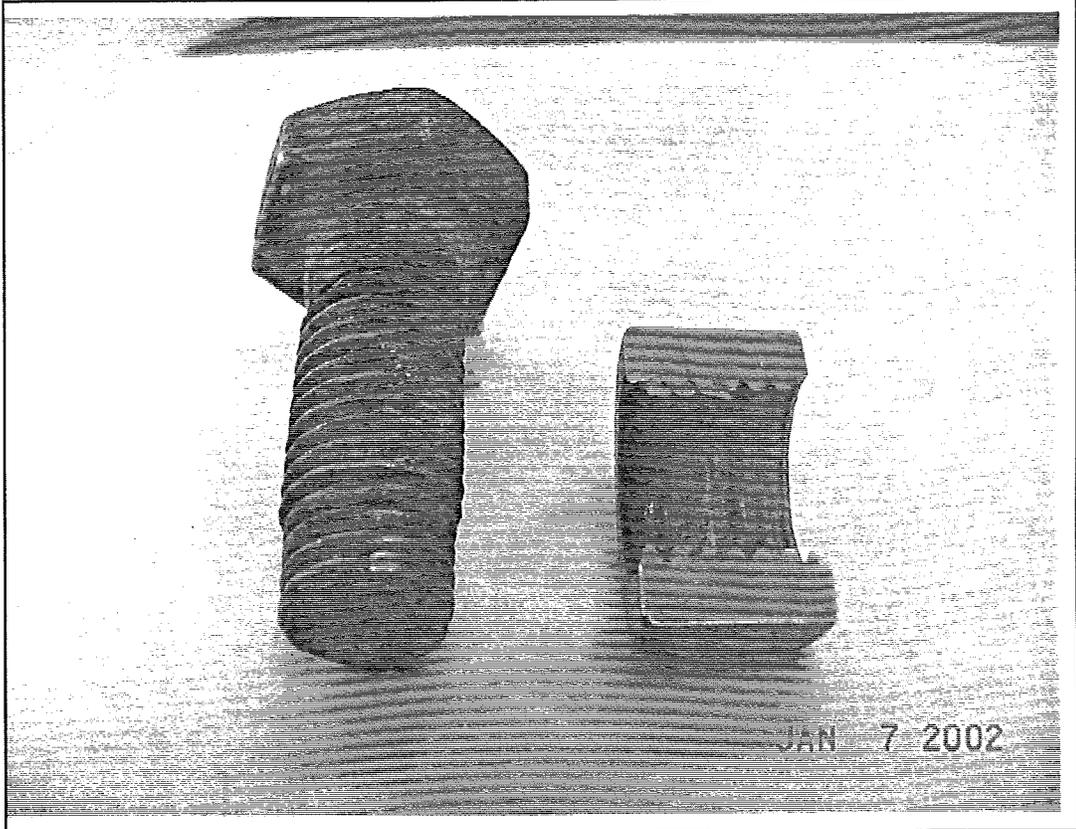


Figure 5 - Photograph of one bolt and nut showing stripped threads.

INSPECTION OF SIGNS ON A-588 BRIDGES

Initial Inspection

To determine if other sign supports were experiencing similar problems, bridges in the vicinity of the failed sign support having A-588 steel beams were inspected. The inspection include structures along I-75 and I-275 in the Metro Region and University Region. Our inspection included unpainted A-588 bridges, having A-588 unpainted sign supports. After inspecting only a few bridges, we learned that missing bolts and pack rust were recurring problems with this type of sign support. It appears that pack rust builds up to a point where the bolt can fracture. Figures 6 through 13 show several sign supports that were found during the initial inspection. The caption with each picture describes the problems found, which included pack rust between the sign support's connection angle and the beam web, as well as missing and fractured bolts.

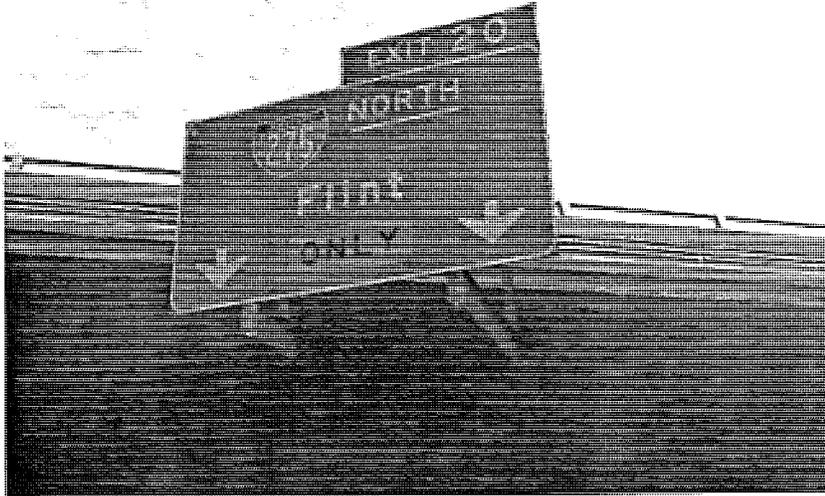


Figure 6 - Structure Number S04 of 58152 (Post Road over I-75). Most of the bolts connecting this sign to the bridge beam were missing (shown in Figures 7 through 9). On one of the angle connections, all of the bolts were gone. The sign was supported by only a few bolts and the vertical hanger straps. The University Region was immediately notified and Department maintenance crews replaced the bolts on the same day.

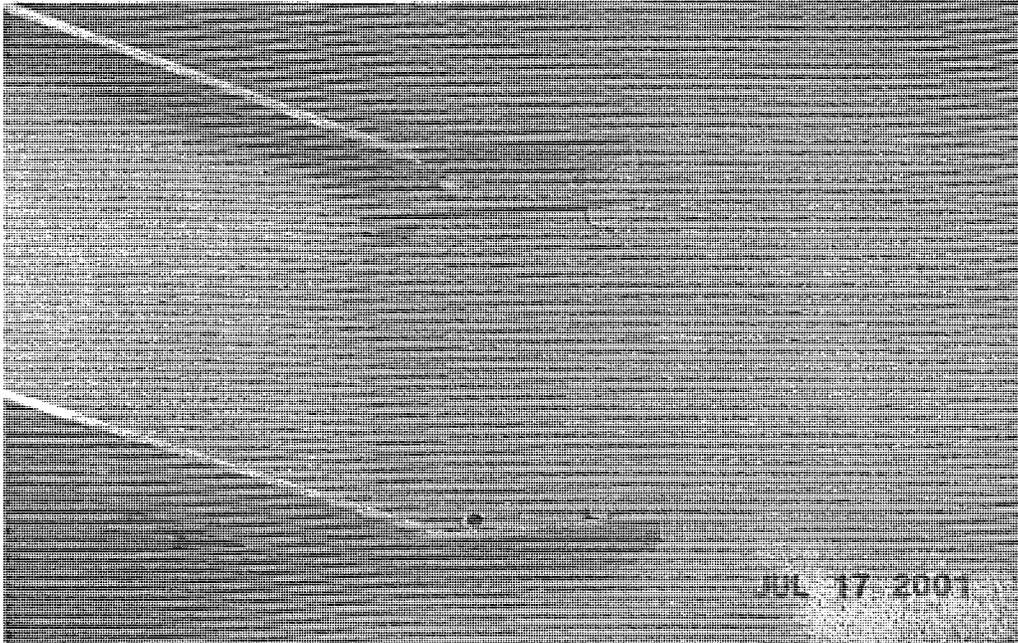


Figure 7 - Structure Number S04 of 58152 (Post Road over I-75). Showing and missing bolts and evidence of pack rust.

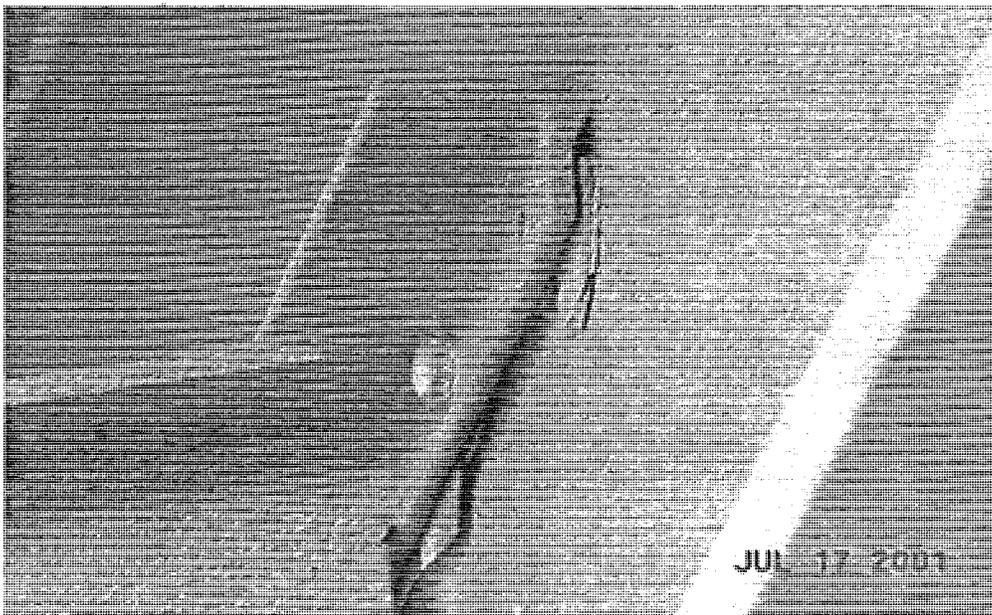


Figure 8 - Structure Number S04 of 58152 (Post Road over I-75). Showing pack rust and the connection angle separating from the beam web, which means all the bolts on this angle are most likely fractured.

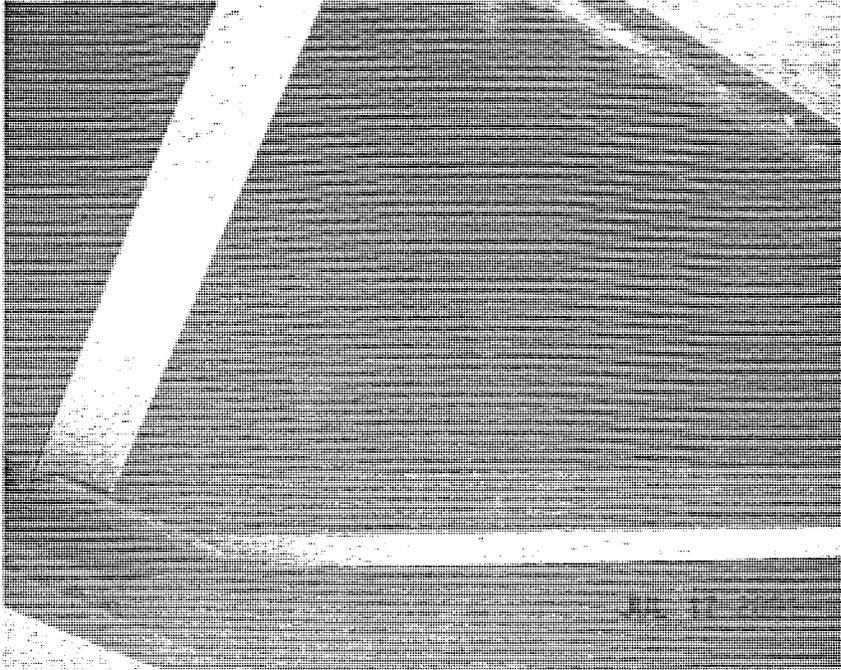


Figure 9 - Structure Number S04 of 58125 (Post Road over I-75). Showing back side of beam web, and missing bolts.

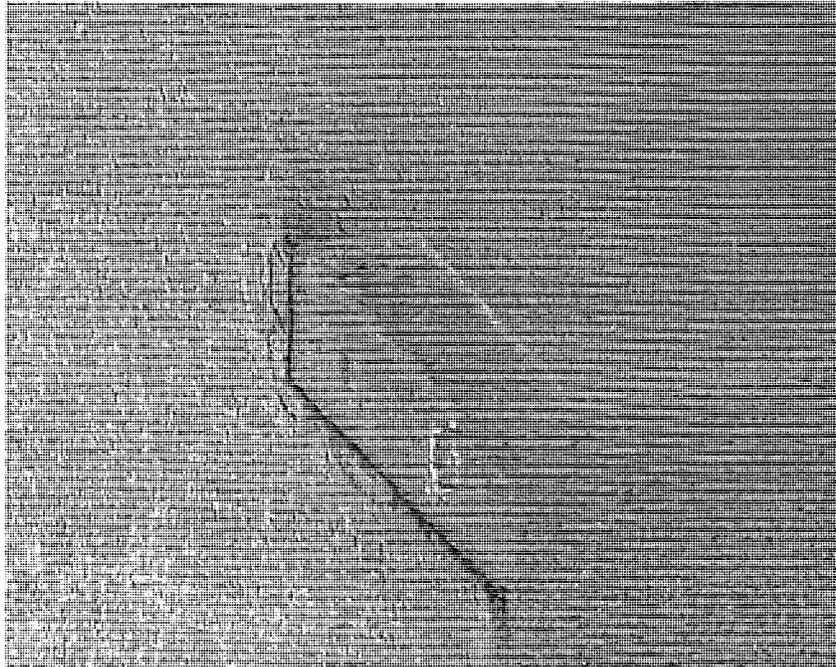


Figure 10 - Structure Number S02 of 82291 (Willow Street over I-275). Showing pack rust and missing bolt.

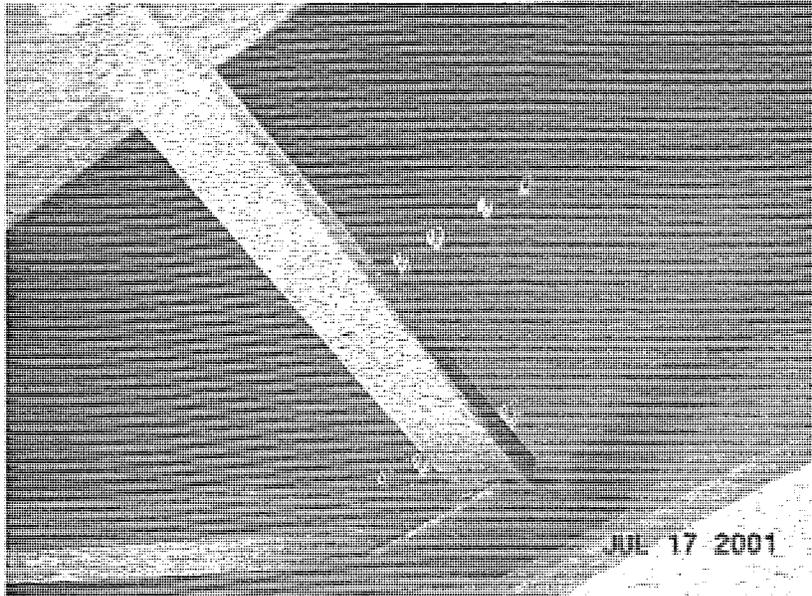


Figure 11 - Structure Number S02 of 82291 (Willow Street over I-275). Back side of beam web, showing missing bolt.

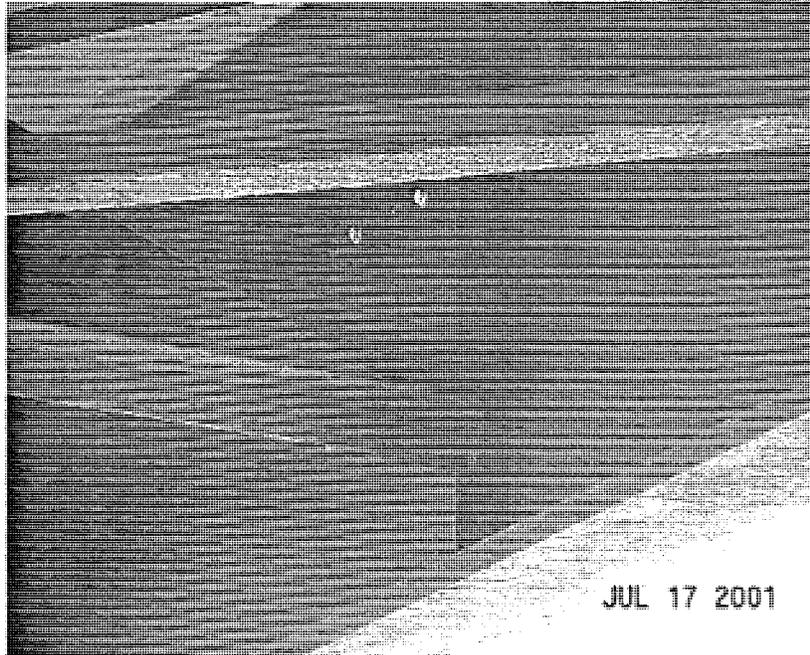


Figure 12 - Structure Number S02 of 82291 (Willow Street over I-275). Back side of beam web, showing missing bolts.

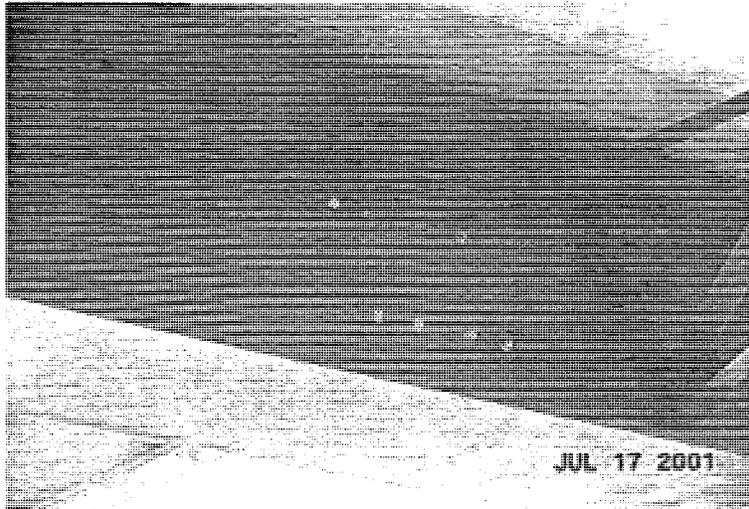


Figure 13 - Structure Number S04 of 58171 (Newport Road over I-275). Showing missing bolts.

INSPECTION OF ENTIRE POPULATION OF SIGNS ON A-588 BRIDGES

Inventory

Because this problem was considered a safety concern, Department management decided that MDOT's entire population of A-588 sign supports on A-588 bridges should be inspected. MDOT's inventory of A-588 bridges (bridges inspected and maintained by MDOT) was reviewed, and a list of bridges was separated into structures within each of MDOT's seven regions. Table 1 shows the number of A-588 bridges in each region. MDOT is responsible for 528 bridges that have A-588 beams. With cooperation from each of the Regions, a schedule was developed for a priority inspection of these bridges. Construction and Technology's Structural Research Unit, with help from the Bridge Operations Unit, inspected bridges in the Metro Region and Grand Region. In the other regions (University, Bay, South West, North, and Superior), regional bridge staff inspected the structures.

Region	Number of A-588 Bridges
Metro	326
Bay	44
University	54
South West	17
Grand	68
North	8
Superior	11
Total	528

Table 1-A-588 Bridge Population

Inspections

A spread sheet was developed to organize and document the inspections. The spread sheet included structure identification, facility carried, featured intersection, location, year built, paint type (for the bridge beams, if painted), date inspected, date repaired (if needed), number of A-588 sign supports and number of galvanized sign supports on the bridge, and comments. The date for A-588 and galvanized sign supports were subdivided into number of signs on the bridge, number of broken bolts, and evidence of pack rust for each type of connection. The spread sheet is available from the Structural Research Unit, and it will be filed with the research project records.

The sign connections were inspected visually from the ground. Binoculars were used to look closely at the connection of the sign to the bridge beams. The back side of the fascia beam was viewed to see if missing bolts could be seen. Looking for missing bolts proved to be the most effective way to locate problem signs, since missing bolts can easily be seen from the shoulder of the roadway.

Inspection Results

Within two weeks, every A-588 bridge was inspected. These bridges had 264 galvanized sign supports and 32 A-588 sign supports. Four of the 264 galvanized supports (2 percent) had problems, such as missing bolts, pack rust, and short bolts. Seven of the 32 A-588 sign supports had welded connections. Of the 25 bolted A-588 supports, 16 (64 percent) had problems such as missing bolts, pack rust, and short bolts. The results for each Region follows:

METRO REGION

On the 326 A-588 bridges in the Metro Region, there were 223 galvanized sign supports and 24 A-588 sign supports. We found 2 galvanized sign supports with missing bolts (one each), and we found two sign supports with pack rust. Several sign supports had welded connections to the bridge beam, and one sign had been hit by a high load. Of the 24 A-588 supports, we found 7 had welded connections. We did not find any problems with the welded connections. Of the 17 bolted A-588 supports, 11 had connections that were experiencing problems. Problems included missing bolts, visible pack rust between the sign support and the beam web, rusted bolts, and short bolts. We could see that several bolts were missing on a very large sign structure. The regional maintenance crew was notified and they promptly replaced all the bolts. When doing this, they found that many more bolts (22 of 44 were actually fractured).

BAY REGION

Seventeen of the 44 bridges had signs attached. All the sign supports were galvanized. None of the signs had missing bolts or evidence of pack rust. One sign support had 3 of 16 bolts non-galvanized (black bolts).

UNIVERSITY REGION

Six A-588 sign supports, and 18 galvanized sign supports were found. None of the galvanized sign supports had any problems. However, six of the seven A-588 sign supports had problems, including multiple missing bolts and various degrees of pack rust. The bolts on each sign support were replaced.

SOUTHWEST REGION

Only four of the South West Region's A-588 bridges had signs connected to the beams. All the supports were galvanized. No broken bolts or pack rust were found. The sign supports, which were recently replaced, were in good condition.

GRAND REGION

Only one A-588 sign support, and two galvanized sign supports were found. No broken bolts or pack rust were found.

NORTH REGION

None of the North Region's 8 A-588 bridges had signs attached.

SUPERIOR REGION

All 11 of the Superior Region's A-588 bridges were either river bridges or railroad structures, therefore none had signs attached to them.

Testing

Bolts from Structure Number S04 of 81062, which carries I-94 over Saline Road were tested in accordance to ASTM A-370, Section A3, "Mechanical Testing of Steel Products, Annex 3.2.1.5 - Tension Testing of Full Size Bolts with a Wedge." The bolts were 5/8-inch diameter, galvanized ASTM A-325 Type 2. Five bolts were tested, achieving tensile values of 33.5, 32.6, 31.7, 34.8, and 34.6 kips. All bolts met the required tensile strength of 27.1 kips. As shown in Figure 14, the failure surface of the tested bolts were similar to the failure surface observed on fractured bolts taken from a sign support, indicating a similar wedge effect produced by the corrosion product. Three tension tests, without a wedge, were also done, with tensile values of 33.1, 33.3, and 32.6 kips, and head displacement values at fracture of 0.171, 0.152, and 0.164 inches. Note that the pack rust measure on the failed sign connection was 0.225 inches, more than enough to fracture the bolts.

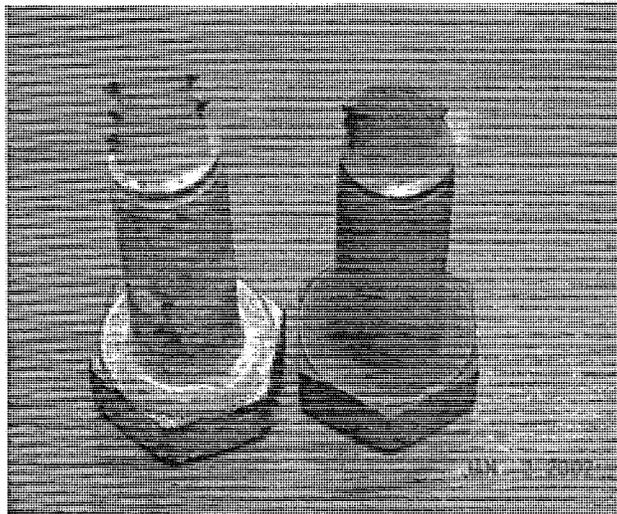


Figure 14Figure 14 - Failure surface of bolts. The bolt on the left is a bolt tested in the laboratory. The bolt on the right is a fractured bolt taken from a sign connection (The galvanizing from the bolt on the right was removed during the cleaning process.).

Analysis

The strength capacity of the beam web to sign support connection was analyzed to see if the bolt design meets the requirements of the American Association of Highway and Transportation Officials (AASHTO), Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals, 1994, and the Standard Specifications for Highway Bridges, Sixteenth Edition, 1996. The bolt design meets the strength requirements, however, the requirement for sealing against moisture penetration was not satisfied. The sign connection angles have a thickness of 3/8 inch, therefore the maximum spacing between bolts should be 5 1/2 inches and the maximum edge distance should be three inches. The spacing of the two bolts on each side of the W-beam section is 5 1/2 inches, but the space between the W-beam section is eight inches. The detail meets the maximum edge distance.

An FHWA Technical Advisory on Uncoated Weathering Steel (A-588) in Structures discusses overlapping surfaces, "if water is allowed to flow over overlapping joints, capillary action can draw the water into the joint and cause "rust-pack" to form. Therefore, the contact surfaces of overlapping joints must be protected from intrusion of rainfall and runoff. This applies to nonslip-critical bolted joints as well as to overlapped joints such as those tapered high mast lighting poles. The faying (contact) surfaces should be painted or sealed to prevent the capillary penetration. In slip-critical bolted splices, "rust-pack" should not occur when the bolts are spaced per AASHTO specification."
(1)

The AASHTO requirements for sealing against moisture penetration are an important consideration when designing connections for A-588 steel. The stiffness of the connection must also be considered. Albrecht (2) found, "...if stiffness of the joint is adequate and the joint is tight, the crevice between two contact surfaces seals itself as corrosion products from around the periphery of the joint. However, if the joint design does not provide sufficient stiffness, continuing crevice corrosion and subsequent accumulation of corrosion products in the crevice induce expansion forces which can deform the connected elements, and cause large tensile loads on the bolts."

For a bolt to develop its required strength it must have full thread engagement, which is defined as: having the end of the bolt at least flush with the face of the nut (3). The sign failure that prompted this investigation, as well as several other sign support connections found during the investigation, had improper thread engagement. Figure 15 shows an example of short bolts. Common industry practice is to specify that two thread pitches must protrude above the top of the nut. This is because, the first few pitches of the thread can be only partially formed because of the chamfer (4).

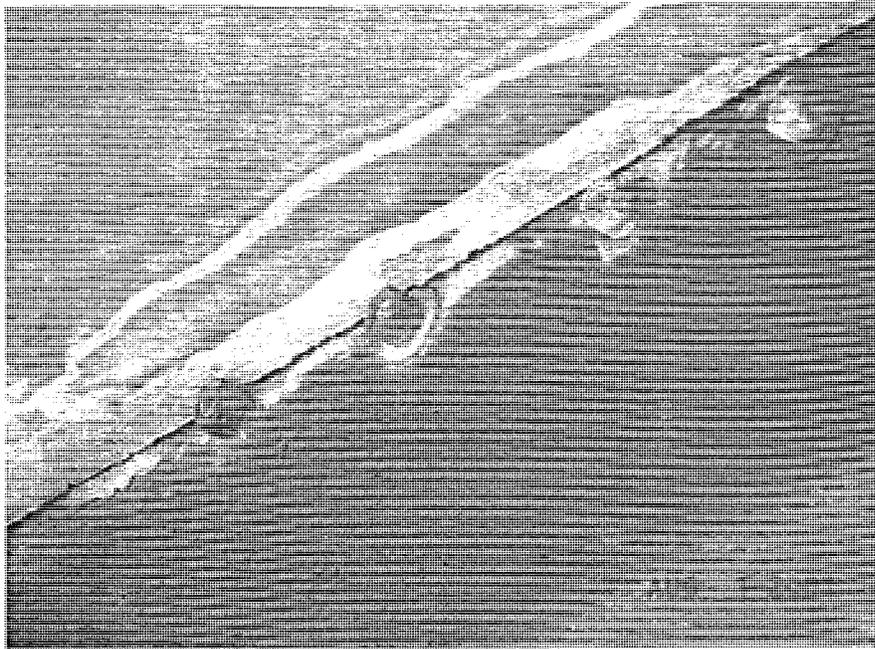


Figure 15 - Showing short bolts.

REVIEW OF INSPECTION PROCEDURES

MDOT Bridge Inspectors were asked about their inspection procedures of sign supports on bridges. Most said that they look at sign supports, but there were differences as to how sign support information was documented on the Bridge Inspection Report. Some inspectors record information about sign supports under the item for utilities. Others record the information under the items for stringers or railings, depending on what the sign support was attached to. Any distinctive elements would be noted under comments for the item it is being included with, or a general note would be provided. If the sign support requires attention a Request for Action would be done, or a note provided under crew recommendations.

CONCLUSIONS

The pack rust that developed between the sign support connection and steel beam web is the result of corrosive action of the unpainted A-588 steel, and the acceleration of the corrosion at the interface of the sign connection and the beam web. The nature of a sign support failure caused by pack rust is best described by Wright (5), "Packout (Pack rust) pressure will slowly increase until the static load in the bolt will be close to or exceeding first yield. Under this condition, a live load stress will result in additional yielding of the bolt. However, this additional yield will cause permanent plastic deformation that will reduce the static pressure due to the pack rust. Additional stress cycles of equal magnitude will not cause additional yielding until the packout pressures again builds up due to additional corrosion."

Pack rust developing between A-588 sign support connections and A-588 beam webs was found to be a recurring problem. An expedited inspection effort undertaken by the Department in the summer of 2001 prevented several overhead sign failures. Of the 25 bolted A-588 sign supports on MDOT bridges, 16 (64 percent) had problems including missing and fractured bolts, pack rust between the contact surface of the sign support and the beam web, and short bolts. Fortunately, on MDOT's 528 A-588 there are only 31 A-588 sign supports (including the welded connections). The A-588 supports were primarily on bridges built before 1974. Bridges built after that date, and sign supports that have been placed or replaced since that time are galvanized steel. However, four of 264 galvanized supports also had missing bolts and pack rust. The problems found on the galvanized steel sign supports were not nearly as severe as the problems found on the A-588 supports; however, bridge inspectors should be aware of the potential for pack rust to develop between galvanized sign support connections when they are attached to A-588 beams.

On painted steel bridge beams, pack rust should not occur since the bridge beam is coated with the Department's three coat paint system prior to the sign being attached to the structure, and the sign connection is galvanized. Recommendations are given in the following section to help prevent pack rust from developing at the connection interface.

RECOMMENDATIONS

Construction and Technology, Bridge Operations Section

1. Provide an item within the Bridge Inspection Report for inspecting sign supports. This will provide a reminder to inspectors to inspect sign supports, and provide a consistent location on the Bridge Inspection Report for documenting this information.

Regions

1. Replace all A-588 sign supports with galvanized steel sign supports. When replacing a sign support the connection interface (faying surface) should be blast cleaned, and primed with organic zinc-rich paint before placing the new connection. The paint shall overlap the perimeter of the connection by 2 inches. The paint color shall be "Brown Weathering Steel," Federal Code Number 10062. Bolts shall be long enough to extend beyond the top of the nut at least two thread pitches. The perimeter of the connection shall be sealed with an approved silicone sealant. High Strength A-325 Type 3 bolts shall be used when attaching a support to A-588 steel.
2. Bridge inspectors should inspect sign supports on bridges for pack rust, missing bolts, short bolts (bolts where the bolt does not project completely through the nut), or impact damage. If the pack rust or missing bolts are discovered, or if the sign support has structural damage, the Regional Maintenance Engineer should be notified, and a close inspection of the sign connection should be done to confirm if pack rust is present or bolts are missing or fractured.

If any bolts are missing or fractured or if pack rust is discovered between the connection interface, all bolts on the support should be replaced and the perimeter of the connection should be sealed with an approved silicone sealant as soon as possible. Depending on the sign support's condition, it should be scheduled for replacement, or the support should be taken down, the connection interface (faying surface on the support angle and the beam web) should be blast cleaned, and primed with organic zinc-rich paint before re-erecting the support. If the beam is unpainted A-588 steel, the paint color shall be "Brown Weathering Steel," Federal Code Number 10062, and the paint shall overlap the perimeter of the connection by 2 inches, otherwise blend the paint to the existing paint. Bolts shall be long enough to extend beyond the top of the nut at least two thread pitches. The perimeter of the connection should be sealed with an approved silicone sealant. High strength A-325 Type 3 bolts should be used when attaching a support to A-588 steel.

Traffic and Safety Division

1. Add the following notes to the Sign Standard Plans VIII-820E and VIII-830E:

When the sign support is attached to A-588 bridge beams the connection interface shall be blast cleaned, and primed with organic zinc-rich paint before placing the new connection. The paint shall overlap the perimeter of the connection by 2 inches. The paint color shall be "Brown Weathering Steel," Federal Code Number 10062. The perimeter of the contact surface of the sign supports connection to the beam web shall be sealed in accordance to Subsection 713.03F of the Standard Specifications.

The bolted connection of the sign support to the beam web shall be according to Subsection 707.03.D.9 of the Standard Specifications.

2. By strength analysis, the bolt design connecting the sign bracket to the beams web is satisfactory; however, adding two additional bolts to each angle would provide additional redundancy to the bolted connection. Figure 16 shows recommended changes to Sign Standard Plans VIII-820E and VIII-830E. The redesign satisfies AASHTO Standard Specifications for Highway Bridges, Sixteenth Edition, 1996, Subsection 10.24. 6.1, Sealing Against Moisture Penetration. The vertical leg of the angle is made longer to allow the bolt to be moved closer to the center of the connection, without interfering with the W-section/angle weld.

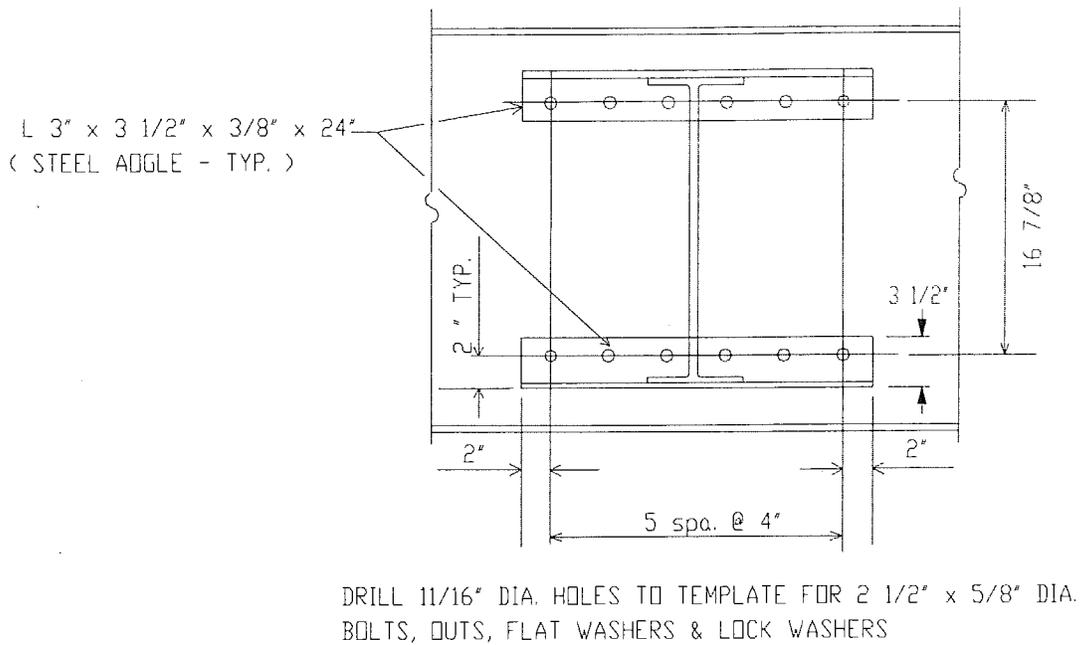


Figure 16 - Recommended Changes to Sign standard Plan VIII-820E and VIII0830E.

References

1. Federal Highway Administration, Technical Advisory T 5140.22, Uncoated Weathering Steel in Structures, October 3, 1989.
2. Albrecht, P., and Naeemi, A. H. Performance of Weathering Steel in Bridges, National Cooperative Highway Research Program, Report 272, pg. 135.
3. Manual of Steel construction, Load and Resistance Factor Design, First Edition, American Institute of Steel Construction, pg. 6-290.
4. Web Page, www.boltscience.com/pages/shortbolting.htm.
5. William Wright, Turner Fairbank - Federal Highway Administration, e-mail correspondence, 1/2/2002.