Tie Girder Fracture in Siouxland Veterans Memorial Bridge

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The Siouxland Veterans Memorial Bridge, from Sioux City, Nebraska, to Sioux City, Iowa, was opened to traffic in January 1981. In May 1982 Iowa Department of Transportation personnel discovered a fracture across the full width of the top flange on the downstream tie girder. The investigation into the cause of the fracture included chemical and physical testing and fractographic and metallographic examinations. Results of the latter examinations showed that the fracture originated at a gas-flame-cut edge of the 2¾-in.-thick A588 flange plate. It arrested at least once at a depth of 0.37 in. and possibly earlier at a depth of about 0.05 in. before propagating in a brittle mode across the flange. The fracture surface was heavily corroded, indicating that the fracture had occurred long before its discovery. The physical tests indicated that the plate in which the fracture occurred did not meet the specified toughness requirements. Additional tests on samples of material extracted from other parts of the girders revealed highly variable toughness properties, some of which did not meet the requirements of the specifications either.

The Siouxland Bridge from Sioux City, Nebraska, to Sioux City, Iowa, a tied arch structure having a span length of 425 ft, was opened to traffic in January 1981. In May 1982 Iowa Department of Transportation (IDOT) personnel discovered a fracture across the full width of the top flange of the downstream tie girder. An investigation to determine the cause of the fracture was undertaken. The investigation included chemical and physical testing and fractographic and metallographic examinations. A summary of the testing and examinations and the authors' opinion of the cause of the fracture are reported in this paper.

BRIDGE DESCRIPTION

The Siouxland Bridge is a steel tied arch structure with continuous-welded plate-girder approach spans. A view of the 425-ft tied arch span, looking south, is shown in Figure 1. As shown in the elevation in Figure 2, the interior panels are 35 ft 0 in. long, and the end panels are 37 ft 6 in. long. The tie girders act in tension to counteract the compressive thrust of the arch, as well as in flexure to resist the live-load bending moment. Panel points are numbered from 0 to 6 to 0′.

A partial cross section of the bridge is shown in Figure 3. The reinforced-concrete deck slab, which carries four lanes of traffic, is supported on nine longitudinal stringers, which bear on the top flanges of transverse floor beams located at each panel point. The floor beams frame into the tie girders at each panel point. The tie girders are supported by 1¾-in.-diameter strand hangers suspended from the arch rib.

The bridge was designed for an HS20-44 loading plus an allowance of 20 psf for a future wearing surface. The design was based on the 1973 specifications for highway bridges of the American Association of State Highway and Transportation Officials (AASHTO), plus their interim specifications, along with the draft version of Guide Specifications for Fracture Critical Non-Redundant Steel Bridge Members and *IDOT SP-229: Special Provisions for Missouri River Bridge.*

The tie girders, shown in Figure 4, are box members that are 2 ft 7½ in. wide by 6 ft 4 in. to 6 ft 5½ in. deep, fabricated from ASTM Grade A588 and A572 steel. The A588 flange plates vary in thickness between 2 and 2¾ in. The A572 web plates are 6 ft deep by ¾ in. thick and are inset ¾ in. from the edge of the flanges. The flange and web plate lengths vary from 8 ft 9 in. to 70 ft, depending on field splice locations. It is believed that the plates were flame cut without preheat. Welded construction was used throughout the tie girders, except for the high-strength bolted field splices. All welded details utilized in the bridge were Category C or better.

Steel for the bridge was provided by two suppliers, one who furnished most of the flange plates, and the other who furnished the remainder of the flange plates and all of the web plates.

EXAMINATION OF FRACTURE SURFACE AND TESTS OF ADJACENT MATERIAL

The fracture was located 6 ft 10 in. north of panel point 3 in the downstream tie girder, and extended in a nearly perpendicular direction across the top flange plate. The view shown

FIGURE 1 Siouxland Bridge at Sioux City, Iowa.

Wiss, Janney, Elstner Associates, Inc., 330 Pfingsten Road, Northbrook, Ill. 60062.

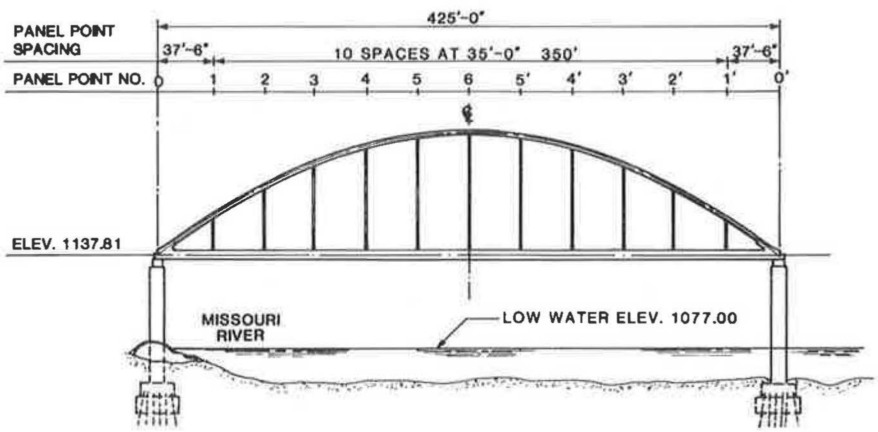

FIGURE 2 Elevation looking west.

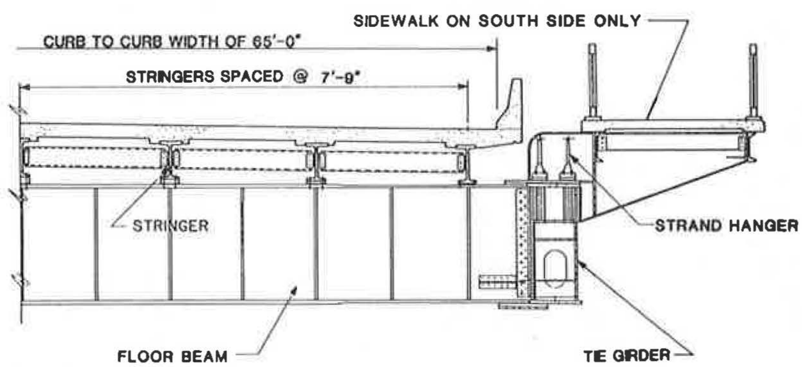

FIGURE 3 Partial cross section.

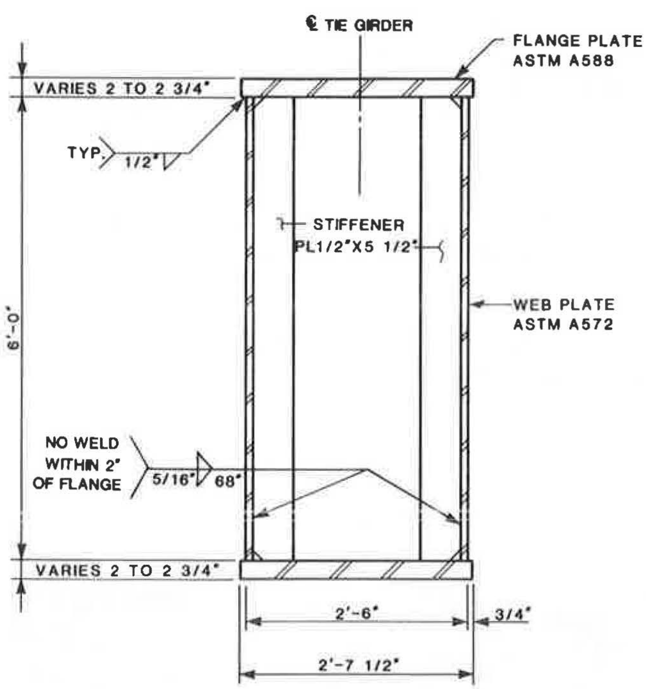

FIGURE 4 Cross section of tie girder at typical intermediate stiffeners.

in Figure 5 was taken as a section of the flange containing the fracture was being cut and removed from the tie girder for laboratory testing. As a precaution against further propagation, IDOT personnel drilled a $^{15}/_{16}$-in.-diameter hole through the weld and web plate on each side of the tie girder to remove the crack tip, as shown in Figure 6. The measured widths of the crack varied from 0.05 to 0.08 in., as shown in Figure 7. There were no stiffeners or any other welded attachments in the vicinity of the crack.

The section taken from the flange is shown in Figure 8. One piece was about 5 in. long (in the direction of the tie girder), and the other was about 9 in. long. The fracture occurred in a region where the flanges and web plates had a fabricated length of 70 ft 0 in.

To preserve the fracture surface, a $^{1}/_{2}$-in.-thick slice adjacent to the fracture was made across the full width of the 9-in.-long piece of flange plate. The remainder was used to conduct chemical, tensile, Charpy V-notch impact, and compact tension toughness tests.

The 5-in.-long piece was given to the supplier of that material, who also removed and preserved a slice containing the fracture surface. Specimens were cut from the remainder for chemical, tensile, Charpy V-notch impact, and hardness tests. The supplier was also given four cores extracted from the top flange near the fracture for testing.

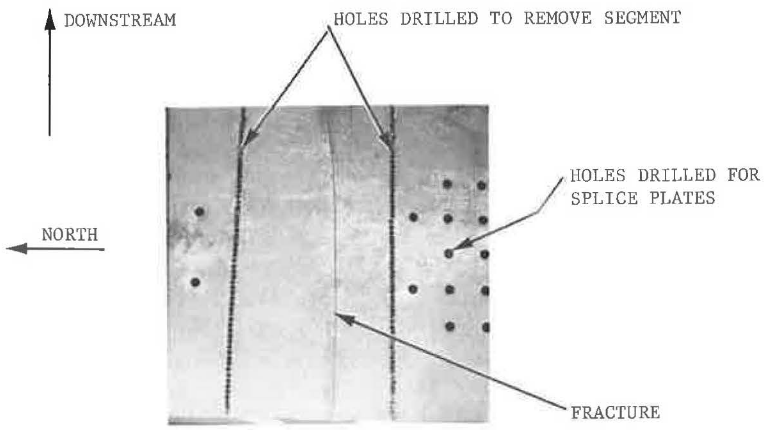

FIGURE 5 Plan view of top flange, showing fracture.

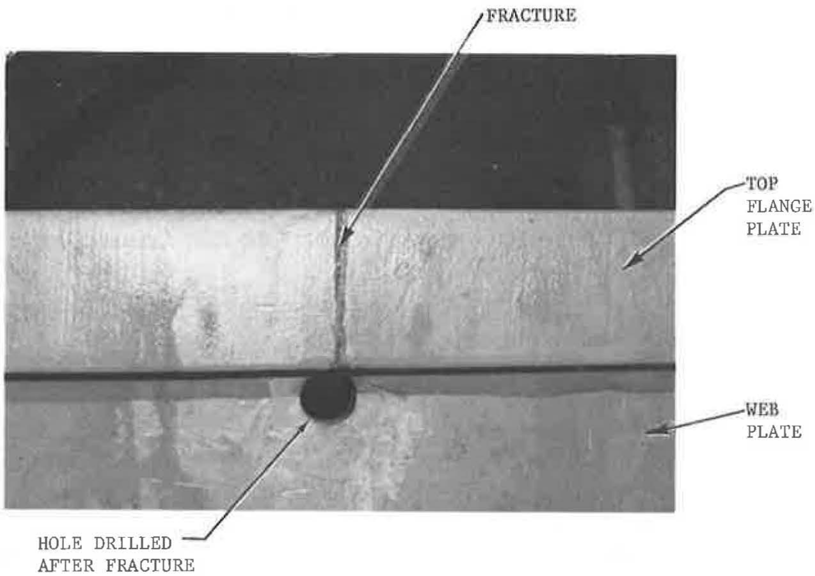

FIGURE 6 Elevation view of fracture.

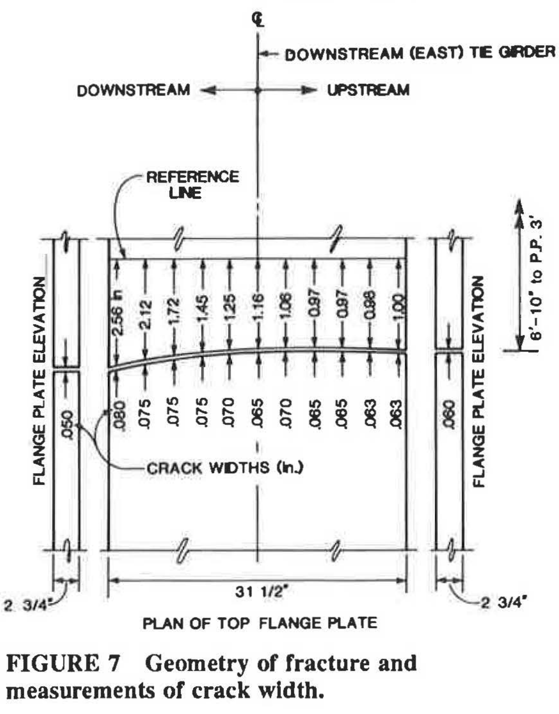

FIGURE 7 Geometry of fracture and measurements of crack width.

Results of tests conducted by Materials Research Laboratory, Inc., on behalf of IDOT and by the supplier were in good agreement. The examinations and findings by the supplier were confirmed by Ed Ripling of Materials Research Laboratory, Inc. All of these test results are summarized in the following sections.

Chemical Properties

The chemical tests indicated that the steel conformed to the requirements of ASTM A588-77a, as specified. Carbon content was at or close to the maximum allowable value of 0.19 percent and the manganese content ranged from 1.10 to 1.15 percent.

Tensile Properties

ASTM A588 requires a minimum tensile strength of 70 ksi, a minimum yield strength of 50 ksi, and a minimum elongation of 19 percent for plates with thicknesses up to 4 in. Tensile tests on longitudinal (rolling direction) and transverse specimens indicated tensile strengths ranging from 90.3 to 103.1

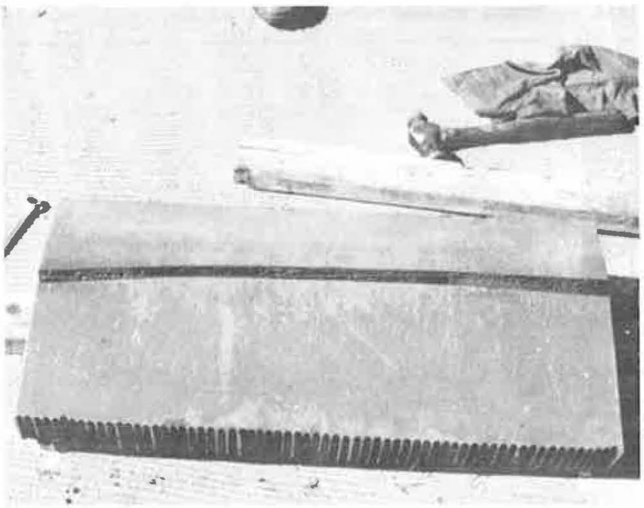

FIGURE 8 Pieces of A588 flange plate with fracture.

ksi, yield strengths from 58.5 to 68.1 ksi, and elongations from 21.5 to 27.5 percent. These results met the requirements for A588 steel.

Charpy V-Notch Impact Tests

Charpy V-notch (CVN) impact tests were conducted on specimens taken at the top, upper-quarter thickness, center, and bottom of the two pieces of flange plate. Specimens from the four cores were taken at the upper- and lower-quarter thicknesses. The tests were conducted in accordance with ASTM A370 at discrete temperature levels from −20°F to 100°F. Results of the tests are plotted in Figure 9. They exhibit significant variability, even for specimens taken from the same location. Of the 27 specimens tested at 40°F, only 5 met the 30 ft-lb minimum requirement of IDOT's special provisions (SP-229).

Plane-Strain Fracture Toughness Tests

Fracture toughness tests were conducted in accordance with ASTM E399, except that a loading rate of about 1 sec to failure (to represent an intermediate strain rate) was used. Three full-thickness compact specimens were cut from the flange plate. The average critical stress intensity factor K_{Ic} at −20°F was 40 ksi $\sqrt{in.}$ The test results were valid according to criteria in E399, except that the fatigue precrack stress intensity of about 27 ksi $\sqrt{in.}$ was somewhat higher than the allowable value of 23.9 ksi $\sqrt{in.}$

Additional tests were performed at 40°F on two smaller half-thickness compact tension specimens machined from the previously tested full-thickness specimens. The K_{Ic} values for these two specimens were about 45 ksi $\sqrt{in.}$, indicating very little toughness increase for a 60°F increase in temperature.

Hardness Tests

Rockwell B hardness tests conducted on a through-thickness section of the flange gave values ranging from 87.5 to 94.5.

Fractographic and Metallographic Analyses

Fractographic and metallographic examinations were conducted to determine the origin and size of the initiating crack and the extension and characteristics of propagation.

A report by the supplier stated that the fracture began in the heat-affected zone of the gas-cut edge of the flange plate on the upstream side of the girder and propagated as a cleavage crack that appeared to have arrested 0.37 in. from the plate edge, and then subsequently from the crack arrest region

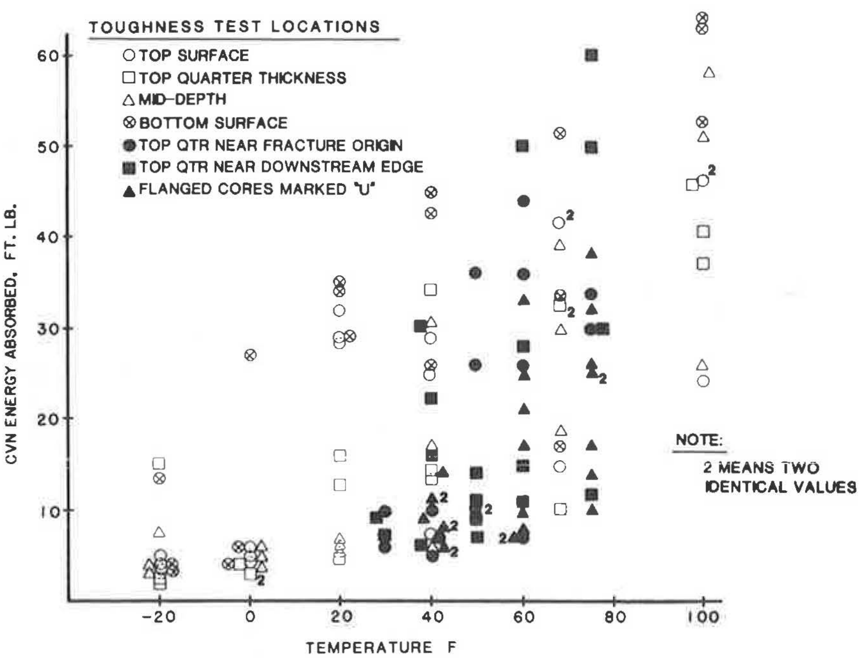

FIGURE 9 CVN test values from flange plate next to fracture.

across the flange width in a cleavage-fracture mode. Figure 10, provided by the supplier, shows the fracture surface.

The report by the supplier also indicated that a magnetic particle examination revealed an additional crack on the downstream edge of the piece of fractured plate. The crack was subsequently shown by metallographic examination to be 0.046 in. deep. It was located within the heat-affected zone of the gas-cut edge on the bottom corner of the plate. The crack surface, shown in Figure 11, exhibited intergranular cleavage and ductile tearing fracture characteristics.

ADDITIONAL TESTS OF FLANGE AND WEB MATERIAL

Because the CVN values for the steel adjacent to the fracture were low, additional samples were extracted from material representing each heat of steel used in the fabrication of the tie girder flanges and webs. All of these tests were conducted by Materials Research Laboratory, Inc., on behalf of IDOT. Initially, 4-in.-diameter cores, identified by the prefix M, were extracted from 16 selected locations. Chemical, tensile, and CVN impact tests were conducted on specimens machined from these cores.

Some of the results of the CVN tests exhibited scatter and thus did not meet the acceptance criteria of Section 22.2.1 of ASTM 370. Consequently two additional M-type cores were extracted for testing. Subsequently, additional cores, identified by the prefix S, were extracted for further material testing. Locations of all cores, including the four cores near the fracture marked U that were initially given to the supplier, are shown in Figure 12.

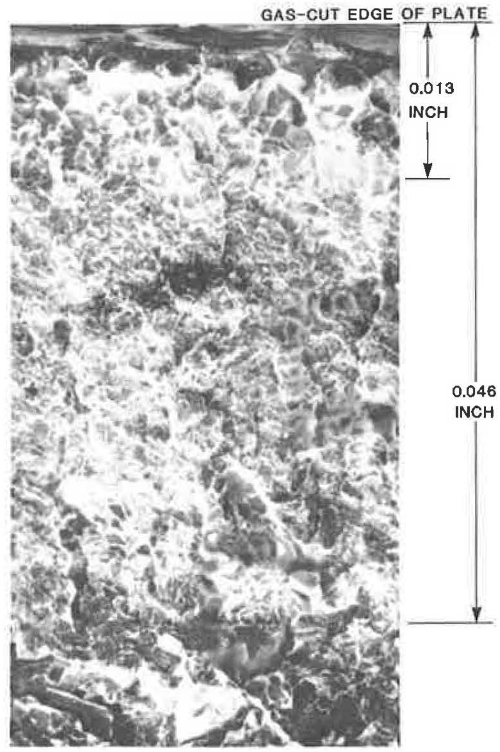

FIGURE 11 Fractograph of crack at downstream edge.

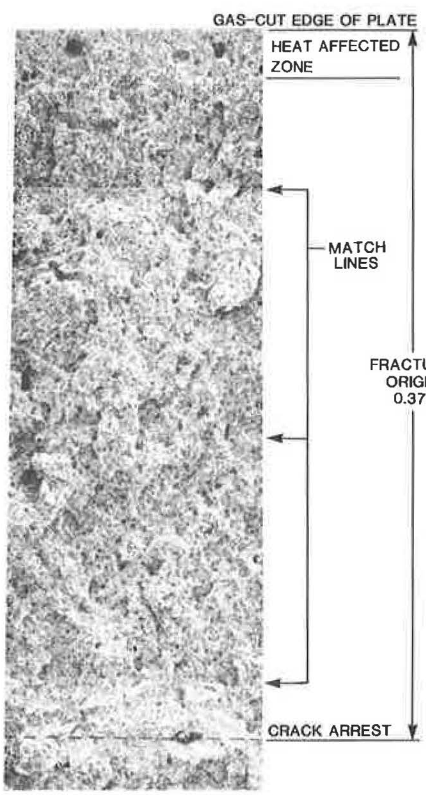

FIGURE 10 Fracture at upstream edge of plate.

Tensile Tests

The results of tensile tests on specimens machined from the core samples indicated that tensile requirements of ASTM A-588-77a were met.

Chemical Tests

Results of all tests met the requirements of ASTM A-588-77a. Carbon and manganese contents of samples from material furnished by the supplier of the fractured plate ranged from 0.16 to 0.18 percent and from 1.02 to 1.17 percent, respectively. Corresponding carbon and manganese contents of samples from material by the other supplier were from 0.12 to 0.15 percent and from 0.85 to 0.97 percent, respectively. Other chemical contents of samples from material furnished by the supplier of the fractured plates that differed from the samples of material by the other supplier were as follows: silicon, 0.34 to 0.43 percent compared with 0.23 to 0.27 percent; nickel, 0.22 to 0.25 percent compared with 0.32 to 0.34 percent; and copper, 0.27 to 0.36 percent compared with 0.22 to 0.27 percent, respectively.

Charpy V-Notch Impact Tests

Specimens were machined from each core, and tests were conducted in accordance with ASTM A370 at temperatures ranging from –20° to 70°F. A plot of the results of the Charpy

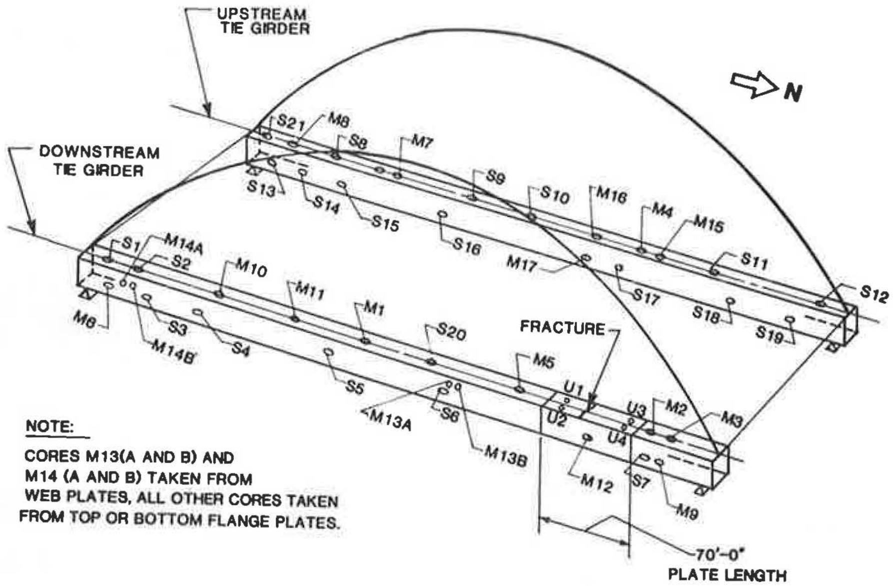

FIGURE 12 Core locations on girders.

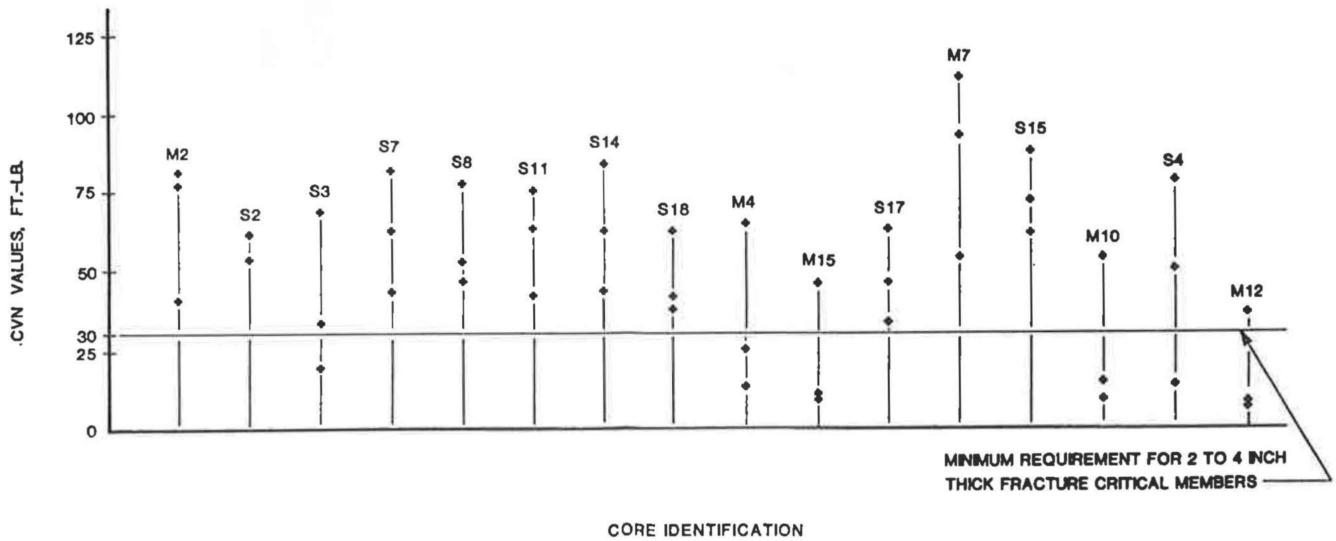

FIGURE 13 CVN values at 40°F for all 2³/₄-in. flange material.

tests for three specimens from each of the 2³/₄-in.-thick cores that were tested at 40°F is shown in Figure 13. CVN values were found to be below the IDOT's SP-229 requirement of 30 ft-lb at 40°F in specimens from six core locations in the 2³/₄-in. plate and five locations in the 2¹/₂-in. plate.

DISCUSSION

The closing of the Siouxland Bridge following the discovery of the fracture imposed a severe hardship on the neighboring communities of Sioux City, Iowa, and Sioux City, Nebraska. The ensuing investigation was carried out expeditiously.

It was immediately evident from the results of the CVN tests on samples from the 2³/₄-in.-thick fractured plate (shown in Figure 9) that there was highly unusual scatter in the toughness properties of this material and that the material did not meet the specified minimum requirement of 30 ft-lb at 40°F. Some of the scatter was related to the position of the test specimen within the plate. According to the mill report for this plate, the CVN values at 40°F were 39, 39, and 43 ft-lb. These observations led to the conclusion that it was necessary to test representative samples of all the steel in the bridge.

As shown in the plot of CVN values at 40°F for all of the 2³/₄-in.-thick flange material in Figure 13, a number of locations were found where the toughness did not meet the specified requirement. Locations where 2¹/₂-in.-thick plates did not meet the requirement were also found. At this point in the investigation, an offer was made to IDOT by the supplier of the fractured plate to replace all flange plates that had been furnished by the supplier. This offer was accepted. Work to replace these flange plates was completed in spring 1983.

The metallurgical examinations were not completed until after work to replace the flange plates was under way. As described earlier, the examinations indicated that a small crack, about 0.37 in. deep, was present in the edge of the flange plate before the fracture occurred. Some time after this plate had been painted, the crack propagated in a brittle mode across the full plate width. Another crack was found, about 0.05 in. deep, in the opposite flame-cut edge of the 5-in.-long piece of removed flange plate. It is believed that a crack of about the same depth had existed initially in the edge of the plate where the fracture occurred.

Alan Pense of Lehigh University provided an explanation for the initiation of a crack due to flame cutting and its extension and subsequent arrest. Stress at the tip of a crack would decrease as the crack propagated out of the zone of high residual stress that is associated with the martensitic material produced along the plate edge by the gas-flame-cutting operation. These residual stresses can be higher than the yield strength of the base material. Therefore, the crack that caused the fracture may have propagated in two stages, first during gas-flame-cutting to a depth of about 0.05 in., and then subsequently (possibly during handling) to the depth of 0.37 in.

When there is an edge crack with a depth of 0.37 in., a stress of about 33 ksi at the crack tip during very cold weather would induce a fracture under traffic conditions (K_{Ic} of 40 ksi $\sqrt{\text{in.}}$ for a loading rate of about 1 sec to failure). Pense pointed out that a dynamic stress at the crack tip of about the same level (not necessarily during cold weather) could also produce a fracture. Considering the heavy corrosion associated with the fracture surface, it is likely that the fracture occurred very early during the life of the bridge. Cracking under these circumstances may have occurred during construction if the bridge had been subjected to an unusual construction loading or during the first or second winter of usage under conditions of an unusually heavy traffic loading.

The fracture may not have occurred in a plate with higher toughness. For example, an increase in K_{Ic} from 40 to 60 ksi $\sqrt{\text{in.}}$ would mean that the stress required at the tip of a 0.37-in.-deep crack to initiate fracture in cold weather would increase from 33 to 50 ksi, an improbable condition.

REPLACEMENT OF THE FLANGE PLATES

To replace the tie girder flanges, it was necessary to relieve the bridge dead load. This was accomplished by temporarily supporting the superstructure on falsework erected in the river. Pilings were driven into the river bottom at four locations to form bents. Two bents were located beneath the expansion joints at panel points 4 and 4′. The other bents were located about 99 ft from the first two, toward each bridge abutment. Longitudinal and lateral beams were erected on top of the bents to provide support for the superstructure.

The dead load was relieved by lifting the superstructure onto temporary support pedestals located under each floor beam. Lifting was accomplished with hydraulic jacks in a computer-generated sequence of lift stages. Stresses in the tie girders were monitored with strain gauge instrumentation. After being lifted, the bridge was tested under a simulated traffic loading and then opened to limited traffic.

The top flange of each tie girder was removed with propane-fueled cutting torches mounted on girder-connected rails running the length of the bridge. This arrangement facilitated accurate cutting of the flange-to-web connection. The cut edges of the webs were ground smooth. The replacement plates were wider than the original plates and were prefabricated with welded side plates located adjacent to the outside faces of the webs. Holes were drilled in the webs through the predrilled holes in the side plates. After the drilling, the flanges were bolted into place. Care was taken to ensure that the internal hanger diaphragms were in contact with the flange plates across their full width.

After installation of the top flange plates had been completed, the bottom flanges were replaced in a similar manner. A reverse jacking sequence was used to remove the support pedestals and retransfer the dead load to the tie girders. The bridge was reopened to normal traffic in May 1983.

SUMMARY

Following the discovery of the fracture in the top flange of the downstream tie girder in May 1982, examinations of the fracture surface and tests of the adjacent steel were made by several parties. The examinations and tests showed that the fracture originated at the gas-flame-cut edge on the upstream side of the tie girder. It arrested at least once at a depth of 0.37 in., and possibly earlier at a depth of about 0.05 in., before propagating in a brittle mode across the flange. The fracture surface was heavily corroded, indicating that the fracture had occurred long before its discovery.

The 2¾-in.-thick A588 steel plate in which the fracture occurred did not meet the toughness requirements of IDOT specifications, and test values exhibited an extreme amount of scatter. Tests on samples of material extracted from other parts of the girders revealed highly variable toughness values, some of which did not meet the requirements of the specifications.

ACKNOWLEDGMENTS

Wiss, Janney, Elstner Associates (WJE) was retained by IDOT as a consultant and to direct the testing. WJE retained the services of E. J. Ripling of Materials Research Laboratory, Inc., Glenwood, Illinois, who conducted all tests made on behalf of IDOT and also made fractographic and metallographic analyses. Ripling, as well as Alan Pense of Lehigh University, also provided consultation. IDOT personnel removed the plate section containing the fracture and extracted the cores from other parts of the bridge.

The authors are solely responsible for the accuracy of the information contained in this paper, and for the findings relating to the cause of the fracture. The contents do not necessarily reflect the views or policies of the Iowa Department of Transportation.

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