Research Report
KTC-10-11/KH 60-07-1F

KENTUCKY TRANSPORTATION CENTER

NONDESTRUCTIVE TESTING OF DEFECTIVE ASTM A 514 STEEL ON THE I-275 COMBS HEHL TWIN BRIDGES OVER THE OHIO RIVER IN CAMPBELL COUNTY, KENTUCKY

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Research Report

KTC-10-11/KH60-07-1F

Nondestructive Testing of Defective ASTM A 514 Steel
On the I-275 Combs-Hehl Twin Bridges over the Ohio River
In Campbell County, Kentucky

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In cooperation with
Kentucky Transportation Cabinet
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Three defective ASTM A 514 steel splice plates were discovered on the I-275 Combs-Hehl twin bridges over the Ohio River. A follow-on in-depth field inspection of 1,356 A 514 steel plates on the bridges revealed 14 additional defective gusset and splice plates. The A 514 steel was improperly heat-treated resulting in a brittle crack-prone microstructure. Ultrasonic and impact hardness tests were used to identify the defective steel. Subsequently, the defective steel plates were either removed or lapped with additional steel plates.</td></tr>
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EXECUTIVE SUMMARY

PROJECT OBJECTIVES AND APPROACH

The main project objective was to conduct field tests on the I-275 Combs-Hehl Twin Bridges over the Ohio River in Campbell County. The tests were needed to identify out-of-spec./defective ASTM A 514 steel. That material was introduced into the bridges during construction some 23 years prior to its initial detection. The presence of the out-of-spec./defective steel was revealed during mechanical tests of cracked splice plates removed from the bridge in early 2008. The defective steel was improperly heat-treated making it excessively brittle and fracture-prone.

Subsequent to that discovery, the Kentucky Transportation Cabinet and FHWA reviewed the issue and determined that all of the A 514 steel should be tested. This included some 1,400 pieces of steel with a weight of about 4.5 million pounds. The Kentucky Transportation Center (in conjunction with technical consultants from IMR Metallurgical Services-Louisville (IMR) and Huntington Testing & Technology (HTT) developed a test protocol for discriminating between the satisfactory and defective A 514 using ultrasonic and impact hardness testing. KTC assembled a field test team along with Mistras/Code Services (providing nondestructive testing personnel), Apex Painting Enterprises (lead paint disposal), Intech Contracting LLC (bridge access/traffic control), IMR (metallurgical consulting/testing) and HTT [nondestructive evaluation (NDE) consulting and oversight].

In early October 2008, field testing began on the twin bridges. The testing progress was slowed due to the discovery of two cracked splice plates at the tower on the downstream truss of the eastbound bridge. That discovery necessitated a change in the testing plan. KYTC posted the eastbound bridge down to a 6,000 lb load limit and posted round-the-clock police surveillance to prevent truckers from using the bridge. Ultrasonic shear wave testing was subsequently performed on similar splice plates at the towers of the other trusses to ensure that they were not cracked.

After ultrasonic testing was completed, the NDE hardness testing resumed focusing first on the upstream trusses. That work was completed in late November. The lane closures were moved back to the downstream trusses which had been partially tested prior to the discovery of the cracked splice plates. Those hardness tests were completed in early December 2008. During the testing, an additional 14 out-of-spec./defective pieces of A 514 steel were detected. None of those were (part-of) fracture-critical members. KTC provided KYTC the list of those pieces. In mid-December 2008, KYTC removed the defective tower splice plates on the eastbound bridge by contract. In 2009, KYTC had a consultant design retrofits for other defective steel that could not be readily addressed by replacement. Beginning in February 2010, KYTC replaced/retrofit all of the remaining defective steel pieces on the two bridges by contract. That work was completed in early June 2010. All of the A 514 steel removed/retrofit was subsequently tested at the IMR laboratory and determined to be defective.

CONCLUSIONS

It is unlikely that the KTC NDE field tests produced any false calls in identifying the out-of-spec./defective A 514 steel. No overcalls were made (as verified by subsequent laboratory testing). The extensive initial and follow-on quality assurance testing including the use of several test methods minimize/eliminate the possibility of any undercalls (i.e. misses). It is probable that all the defective A 514 steel on the two bridges has been detected and addressed.

The steel furnished to ASTM A 514 did not meet that specification due to mechanical properties, not chemical composition. The steel supplier did not properly temper 17 plates used in the bridge. The cracking in 5 of the 17 plates with the out-of-spec. steel is an indicator of the severity of this defect. Several exhibited stress corrosion cracking/hydrogen stress cracking which is not anticipated in ASTM A 514 steel (12). The inadequacy of these plates is indicated by the fact that none of the 1,339 plates of acceptable A 514 steel, including those that were welded, showed any signs of cracking. The out-of-spec. plates were defective both in required mechanical properties and in actual field performance.

During this project, it was determined that some of the filler plates used in conjunction with the lower chord splice plates did not have the same thickness as the gusset plates to which they were attached. That deformed the splice plates and probably contributed to cracking in the 3/8" lower chord splice plates. The differences in thicknesses between the filler plates and gussets may have contributed to the fracturing of the out-of-spec./defective splice plates, but only because the steel was defective. Other lower chord splice plates at similar locations that were made of acceptable A 514 steel did not crack.

RECOMMENDATIONS

The following *recommendations* are provided:

1. KYTC has funded a related SPR study, KYSPR 09-401 "Kentucky Bridges with High Strength Quenched and Tempered Steel." The purpose of that study is to identify other KYTC bridges with QT steel in case similar problems should arise on those bridges. *KYTC should retain a list of those bridges and conduct hardness tests on the QT steel if cracking problems are detected in the future.*
2. On this project, the NDE testing appears to have been effective in discriminating between acceptable and defective A 514 steel. However, with any NDE testing, some caution is always advisable in moving forward. *In about 5 years, KYTC should conduct an "arms length" inspection of all A 514 steel on the I-275 Combs-Hehl Bridges and repeat that type of inspection every 5 years thereafter.*

SYNOPSIS

All of the out-of-spec./defective ASTM A 514 steel on the I-275 Combs-Hehl Twin Bridges has been detected and replaced/retrofit. The remaining ASTM A 514 steel should be periodically inspected to ensure no other problems arise. KYTC should determine whether it can/should seek restitution for the remedial work from the steel manufacturer.

1. INTRODUCTION

1.1 BACKGROUND

The East crossing of I 275 over the Ohio River is comprised of the Combs-Hehl twin bridges possessing 1,400-foot cantilever through truss spans (Fig. 1). The bridges were designed in 1974, with the trusses designed by Sverdrup & Parcel and Associates. The bridges were constructed in 1979 at a cost of $30,500,000 by the American Bridge Corporation. Each bridge has three traffic lanes and two curb lanes. Combined they carry over 80,000 vehicles per day. In the Cincinnati area these bridges were once used to carry super loads between Ohio and Kentucky. The bridges are maintained by the Kentucky Transportation Cabinet. (KYTC)

The twin bridges incorporated the "Family of Steels" design concept incorporating four different ASTM steels in the steel trusses: A 36, A 572, A 588 and A 514 (1). ASTM A 36, A 572 and A 588 are hot rolled structural steels. The strongest of these steels, ASTM A 514, is a low alloy quenched and tempered steel with a minimum specified yield strength of 100,000 psi, a minimum tensile strength between 110-130,000 psi and an minimum elongation of 18 percent (for plate thicknesses less than 2 inches (2). This steel was primarily utilized where high tensile strengths were required. It was used in gusset and splice plates and in welded box members that comprised chord members, posts and diagonals in the trusses (Figure 2). Together, the bridge trusses incorporated a total of 4,500,000 lbs. of A 514 steel.

1.1.1 Bridge Steel Cracking and Subsequent Analyses

In the fall of 2006, an engineering consulting firm conducting a fracture-critical inspection on the bridge, detected cracks in three splice plates on the lower chords of the westbound bridge (3). Two of the cracked splice plates were located at L12 and L12' on the upstream truss. The third was located at L12' on the downstream truss (Figure 3). The plates measured 3/8" x 31" x 37". The endpoints of the cracks were marked and the splice plates periodically monitored for crack growth. Over time, technicians observed significant crack growth (Figure 4). KYTC officials decided to replace the cracked plates. That work was accomplished under contract in late May 2008 (Figure 5).

The Kentucky Transportation Center (KTC) at the University of Kentucky was charged with monitoring the plate removal operation and providing failure analysis of the cracked plates. The work was funded under Kentucky Highway Investigative Task (KHIT) 60 "Investigation of Voids/Cracking on the I-275 Twin Bridges over the Ohio River in Campbell County-Phase I". The plates were taken for evaluation to IMR Metallurgical Services-Louisville LLC, a firm located in Louisville, Kentucky, specializing in materials testing and failure analyses. KTC personnel directed IMR to conduct chemical analyses, mechanical testing, metallography and fractography on the fractured plates (See Appendix A). From the plans, the splice plates were determined to be made from ASTM A 514 high-strength quenched and tempered (Q&T) steel (also referred to as A 514 steel). The chemical analysis (by optical emission spectroscopy per ASTM E 415-99a and combustion analysis per ASTM E1019-03) of the steel plates indicated that they conformed to A 514 (Table 1). The chemical composition for the three plates was nearly identical indicating that they probably came from the same heat.

Mechanical testing of test specimens cut from the plates revealed that those properties did not conform to A 514 specifications (tensile testing per ASTM E8-04 and Brinell hardness testing per ASTM E10-07a). The steel had exceedingly high tensile and yield strengths coupled with low elongation values compared to those specified (Table 2). Charpy V-notch impact tests were performed (per ASTM E23-04) on test specimens cooled to 0° F, specified for AASTHO temperature Zone 2. The Charpy tests produced extremely low values compared to those currently specified for ASTM steel. Visual examination of the steel microstructure revealed that it was improperly tempered (Figure 6). The laboratory results indicated that all three fractured plates were comprised of extremely hard, brittle steel unsuitable for bridge service. The close correspondence of the chemical and mechanical properties indicated that the plates probably came from the same heat of steel.

Significant uniform corrosion was observed on the faying surfaces of the plates. Metallography of sections taken at the faying surfaces revealed extensive pitting caused by the corrosion. Ion chromatography was performed on the corrosion products (per ASTM D4327-03) for water soluble anions. Chlorides (4020 ppm), Sulfates (3640 ppm), nitrates (380 ppm), phosphates (80 ppm) and nitrites (188 ppm) were detected. On the polished specimens small intergranular cracks were observed emanating from some of the corrosion pits. Additionally, intergranular branching cracks were observed on a polished section taken at the cracked edge of one plate (Figure 7). These results indicated that the plates were susceptible to stress corrosion cracking/hydrogen stress cracking (SCC/HSC). This was an added concern as the cracks from stress corrosion were generated from the backside of the plates and would not be visible until they had penetrated across the full thickness of the plates. Energy dispersive X-ray spectroscopy (EDS) testing revealed the presence of both calcium and chlorides on the corrosion surfaces on the backsides of the splice plates. It is presumed that chlorides penetrated the interface between the splice plates and filler or gusset plates, promoting corrosion which generated hydrogen resulting in the intergranular cracking.

Scanning electron microscope fractography was hindered by the extensive corrosion products on the fracture surfaces. Shear lips were observed on most of the fracture surfaces, sometimes on both sides of the plates. Stress corrosion/hydrogen-induced stress cracking was suspected as a cause of the cracking, but additional subcritical crack growth could have been caused by fatigue once the cracks had nucleated. Wrought structural steels typically have microstructures providing yield strengths well below 150,000 psi that are not normally susceptible to SCC/HSC. The impact of the improper tempering on the ASTM A 514 steel in the splice plates was to provide SCC/HSC-prone microstructures.

IMR/KTC reported the results to KYTC officials in August 2008 (4). They recommended that all of the A 514 steel on both bridges be tested to detect any remaining out-of-spec./defective steel followed by remedial actions (e.g. replacement of defective steel). One challenge was identifying a reliable method to distinguish between compliant and out-of-spec./defective steel. Another was to address this problem prior to the onset of winter. IMR Charpy tests of the defective A 514 steel indicated a lower shelf impact toughness (10-12 ft-lb) beginning at about 30 ^{o}F. This meant that the steel was more susceptible to brittle fracture in winter months when the bridge steel would be cold. FHWA testing indicated that the steel was so brittle, that lower shelf fracture toughness values would prevail in any season (5). In other respects, the FHWA report concurred with the findings and recommendations of the IMR/KTC analyses. IMR/KTC investigators remained concerned over the possibility that winter temperatures could prove problematic for the steel and proceeded with haste to establish a test program that could be completed prior to the lowest winter temperatures.

KTC prepared a Phase II study under KHIT 60 to identify the best method for identifying the out-of-spec./defective steel and otherwise scope the inspection work. The proposal was submitted to KYTC and approved in early September 2008. The study was approved and work proceeded with the intention of initiating the field testing in late September/early October.

1.1.2 Developing Test Procedures to Detect Defective Steel

IMR and KTC personnel determined that the improper heat-treatment that resulted in the brittle A 514 steel also resulted in higher tensile strengths (See Table 1). Tensile strength can be measured indirectly by indentation hardness testing. Indentation hardness (for this particular steel) was expected to be inversely proportional to Charpy values. To investigate this possibility, IMR took samples of the defective steel and heat treated them by re-austenizing, quenching and subsequent re-heating of different samples at various tempering temperatures (Figure 9). This produced a range of indentation hardness values that were inversely proportional to impact strengths (Figure 10). This indicated that indentation hardness testing should be suitable for separating acceptable from defective A 514 steel.

Two approaches were initially investigated for field hardness testing-eddy current and portable field hardness test methods. Eddy current testing would involve applying a probe with wire windings on a test piece, creating an electric field and lifting the probe off the test piece surface to break the field. There were several potential portable hardness methods (e.g. indentation, rebound, impact, ultrasonic) to be considered.

KTC involved Huntington Testing and Technology-Louisville (HTT), a local nondestructive testing firm experienced with both eddy-current and ultrasonic hardness testing to assist with the evaluation of the two test methods. The General Electric Corp. (GE) was involved peripherally as it had recently acquired Krautkramer, a German firm that manufactured both types of nondestructive testing devices. GE provided an eddy current tester for evaluation as a test method to discriminate between acceptable and defective A 514 steel. HTT provided the Krautkramer *MIC 20* ultrasonic hardness tester used to evaluate the capability of that test method). The unit had a 10 kgf probe that was pressed against the test piece (Figure 11). It possessed a LED screen to display the hardness value of each test and could take running average of multiple tests (Figure 12).

To discriminate between acceptable and defective A 514 steel, acceptable A 514 steel was acquired from a steel wholesaler in a grade (B) approximating the same elemental constituents as the defective steel (e.g. approximating the same grade of steel). IMR conducted elemental and mechanical tests to characterize the acceptable steel. Then eddy current and ultrasonic hardness tests were conducted on both the acceptable and defective steels to determine the suitability of the two test methods. The eddy current method did not prove satisfactory.

Laboratory testing of both acceptable and the defective A 514 steel plates indicated that hardness testing by the ultrasonic contact impedance method (per ASTM A 1038-05) was acceptable. This method used a diamond indenter on the end of a steel rod. The rod is excited in an ultrasonic longitudinal oscillation by a piezo-electric crystal at a frequency of about 70 kHz (when the rod is in air). When the diamond indenter/rod is pressed into a material at a fixed/known force, the resonant frequency of the rod will change. The hardness can be determined from the frequency shift between the rod resonating with the indenter in air and subsequently resonating with the indenter embedded in the test piece (at a fixed force). The ultrasonic hardness test provided consistent ultrasonic hardness Rockwell C values of 25-26 for the acceptable steel and 40-42 for the defective steel. The decision was made to use ultrasonic hardness testing. Among the desirable features of ultrasonic hardness testing identified by KTC/IMR personnel were: 1) the ability to provide readings that corresponded with bench hardness testers, 2) the ability to readily discriminate between acceptable and defective A 514 steel, 3) the ability to take multiple hardness readings in a short time period, and 4) the ability to provide direct readings in related hardness units (e.g. Brinell or Rockwell C hardness numbers). After these tests, ultrasonic and conventional indentation hardness test values were not distinguished from each other.

The ultrasonic test required a flat steel surface requiring paint/mill scale to be removed by grinding. The as-rolled finish of all of the A 514 steel was not mirror-flat and contained occasional surface-breaking voids. These caused variations in the ultrasonic hardness tests. However, those variations could be addressed by conducting several initial tests to determine the prevalent ultrasonic hardness values and thereafter by eliminating outlier values. A test was considered complete when 10 consistent readings (all within a few HRC numbers) were obtained.

The *MIC 20* needed to be calibrated initially and suitable hardness blocks were obtained using pieces of the acceptable and defective A 514 steel. The HRC values for the calibration blocks were determined by bench indentation hardness testing using a calibrated bench tester at IMR.

The bridges were termed westbound (downstream structure) and eastbound (upstream structure) denoting the directions of vehicular traffic (westbound from Ohio into Kentucky and eastbound from Kentucky into Ohio). The structures were symmetrical about center piers that contained towers (panel point 16) from which the trusses were cantilevered. The panel points were numbered sequentially decreasing from the towers to the ends of the trusses. On the Kentucky side the panel numbers were denoted by plain numbers (i.e., 1, 2, 3…, 15). On the Ohio side the panel numbers were denoted by apostrophes (i.e., 1’, 2’, 3’…, 15’). That numbering was based upon the terminology used in the KYTC bridge plans. The trusses were identified as upstream (north side) and downstream (south side) related to the prevailing flow of the Ohio River. For bridge steel, upper horizontal plates were termed “top” and lower horizontal plates were termed “bottom”. For vertical plates, those nearer the roadways were termed “inboard”. Those on the water side were termed “outboard”. Splice plates along the chords were termed “external” for ones on the outside faces of the chord box members. Those mounted inside the box members were termed “internal”.

1.2 TEST PROTOCOL PREPARATION

Review of the plans identified about 1,400 pieces that contained A 514 steel on the two structures. Some of the plans were unclear about the types of steel used at several locations. Eventually, field tests revealed that some plates were not made from A 514 and the total number eventually was 1,360 pieces for the four trusses. The A 514 steel was located entirely on the trusses, not in the floor system or transverse elements (Figure 13). Away from the towers, the A 514 was primarily located on the upper and lower chord members. At the towers, the A 514 was located on the upper and lower chords, diagonals and the tower itself. Numerically, most of the A 514 was employed as single pieces - gusset plates or splice plates. However, from a total weight perspective, most of the A 514 was employed in welded box members that comprised portions of the upper and lower chords. Bolted internal stiffeners made from A 514 steel were located inside the box members. Those were ignored as they were considered non-critical. The box members were considered to be comprised of four plates (top, bottom, inboard and outboard). Welding was not considered a problematic issue as long as none of the chord member plates was found to be made from defective steel or cracked.

The next step was to determine an acceptable test protocol. Based upon ASTM A 514 specifications, acceptable steel had a Brinell hardness of 235 to 293 BHN corresponding to ~21 to 31 HRC (6). The decision was made to consider defective plates; those with HRC>32 as hardness values typically could accurately be measured to ± 1 HRC. A second decision was to perform ultrasonic hardness tests on two locations on each A 514 plate (A and B). If the average hardness values varied such that a test at one location passed a plate and a test at the other failed it, a third test would be performed at a third location to determine whether a plate was satisfactory or defective. This proved a non-issue as the plates either clearly passed or failed the hardness tests with both trials.

Once the test program began, some inconsistencies were encountered in testing the out-of-spec./defective steel. Due to this issue, a second hardness test method was desirable to confirm the results of the ultrasonic hardness testing. An impact hardness test was employed for final hardness evaluation (ASTM E 10). The unit selected was the Teleweld *Telebrineller* (7). The unit consists of a sleeve of square cross-section into which a square steel bar of a known hardness is inserted (Figure 14). The sleeve contains a cut-out in which a hard ball bearing is encased in rubber. On the opposite face of the sleeve is a steel anvil that bears on the steel bar. The ball bearing contacts the steel bar and also the surface of a test piece. A hammer is used to strike the anvil forcing the bar against the ball bearing which, in turn, bears against the test piece. After the impact, the NDE technician measures the diameters of the ball bearing indentations in both the bar and the test piece (Figure 15). The hardness of the test piece is calculated to be the product of the known hardness of the bar times the ratio of the square of the respective indention diameters (bar dia.^{2}/test piece dia.^{2}). This test method was significantly slower than the ultrasonic hardness testing, but less susceptible to variability. The resulting test provided hardness readings in Brinell Hardness Numbers (BHN) units and compared the Rockwell C units (HRC) employed for the ultrasonic hardness and laboratory bench tests. Fortunately, conversion tables are available to translate between the difference hardness values (8). The *Telebrineller* was used on all A 514 plates with average ultrasonic hardness test values ≥ 25 HRC. Two tests were to be conducted on each piece of questionable steel.

The final step in protocol preparation was to accommodate the NDE technicians (who would probably be unfamiliar with bridges) and provide several forms of documentation for test results. The plan review included numbering of all of the A 514 plates (per truss) and the preparation of a spread sheet with the plate/piece number, a description and the provision for test results (Table 3). These were subsequently provided in paper form to NDE technicians to enable them to locate and identify test pieces. Sufficient copies of plans were made to provide a copy for each NDE technician and the project oversight staff. Plans were hand-marked to locate all of the A 514 steel pieces. The technicians were required to fill out a hard-bound test log documenting their daily work including starting and finishing times, equipment calibration readings, test locations, test plate numbers and test methods/results. These were to be reviewed periodically by HTT as part of its NDE project oversight work (described in the next section). The technicians were also to document each test pictorially. They were given paint markers and digital cameras to mark results adjacent to each test site and take pictures of the site/markings (Figure 16). If issues arose subsequent to testing, KTC/KYTC personnel could access a test site and ascertain where a test reading was taken.

Over the course of the work, a few steel plates identified by KTC investigators as being A 514 steel were found by the NDE investigators to be other types of steel. KTC investigators originally identified the A 514 pieces from the bridge plans. When uncertain about the steel type, KTC investigators elected to call them A 514 steel. The spread sheet was updated when these mistakes were discovered and the mis-identified plate numbers were discarded leaving several gaps in the previously consecutive plate numbering system.

2. WORK TO IDENTIFY DEFECTIVE A 514 STEEL

2.1 PROJECT DEVELOPMENT AND MOBILIZATION

Having identified an acceptable test method and protocol, the next task involved obtaining necessary qualified test personnel, field access equipment/operators, paint personnel, traffic control expertise and experienced bridge site supervisors. This work took place over a compressed time interval as KTC and IMR wished to initiate the field testing as soon as possible.

HTT was contracted to provide several NDE technicians along with training of NDE technicians and oversight for NDE aspects of the project. The training/qualification was administered by a senior ASNT Level III supervisor from HTT. He was also charged with weekly visits to the job site to oversee test operator work/equipment/ recordkeeping. HTT also provided a limited amount of equipment used on the project. Mistras Inc., formerly Conam Testing/Code Services, provided most of the NDE technicians who were contract workers. Mistras also supplied the bulk of the NDE equipment leased from GE and other NDE equipment suppliers.

Paint expertise for waste disposal (the existing paint that needed to be removed for the testing contained lead) was provided by Apex Painting Enterprises, a local test firm experienced with environmental and other issues related to bridge painting. Apex also furnished technical assistance for proper paint removal, waste collection (including hazardous waste permitting) and repainting of the test patches once the work was completed.

Intech Contracting provided the field support including traffic control, field oversight, access equipment/operators, support personnel including workers tasked with paint removal and subsequent repainting and several climbers who were needed to access/test at some upper chord locations inside the box members. Intech supplied several snooper-vehicles for below deck testing on lower chord elements and man lifts for testing above deck level. That equipment was necessary for the bulk of the testing, though a few steel plates could be accessed from the central bridge piers.

IMR was used on the project to assist with technical (metallurgical) aspects of the project. They prepared the calibration blocks and also provided a site for initial qualification training of the technicians. Later, they assisted by investigating several problematic issues that arose related to the field testing. They also received all defective steel when it was removed from the bridge and took samples of defective steel plates that was remedied, but not removed. All the defective plates/samples were subjected to bench indention hardness testing by IMR. The firm also retained all of the defective steel/samples for follow-up resolution of this issue.

The field testing was to be conducted as a joint state/federal project. An initial amount of $1,000,000 was requested to cover the testing costs. KHIT 60 was given a Phase III to fund KTC overall project oversight and administration work. After receiving a letter from KYTC stating that this was an emergency contract, KTC was able to avoid the competitive bidding process normally mandated by University of Kentucky regulations. That shortened to project development time by 2-4 weeks.

The contracted firms were given several weeks to mobilize with the target date for the onset of field work being the first week in October. Intech was able to mobilize sufficiently to begin field work several days sooner than scheduled. KTC coordinated the field work with KYTC Central Office (Maintenance) and District 6. KYTC in turn cooperated with the Ohio DOT concerning the requirements and establishment of lane closures on I 275 for traffic from Ohio entering the Westbound Bridge. District 6 assisted with lane closure requirements on I 275 for traffic from Kentucky entering the Eastbound Bridge

2.2 FIELD TESTING

The test plan included the use of full long-term lane closures on the outside lanes (and subsequently the inside lanes) to allow the use of access vehicles for testing steel on the four bridge trusses. Intech was to provide and maintain the lane closures. The initial plan was to set up on the downstream curb lane of the Westbound Bridge and upstream curb lane of the Eastbound Bridge. Thereafter, the work would progress across those trusses from end-to-end until completed and then the lane closures would be shifted at night to the opposite curb lanes to permit testing of the opposite trusses.

While HTT could temporarily supply several NDE technicians, the main source of inspection personnel was Mistras Services. As working at heights was required, it took several weeks to conduct a nationwide search by Mistras to locate suitable technicians.

This delay enabled KTC, IMR and HTT to prepare a day-long training program to familiarize the Mistras personnel with the bridges, test equipment and test protocol. HTT technicians were the first to receive that training. It also allowed HTT to have several technicians working early on to resolve any unforeseen problems related to site conditions, the test equipment and the test protocol. This slow start-up also enabled Intech to train new personnel for test patch preparation, working with leaded paint and operation of access equipment. The Intech site preparation personnel were to use the available access equipment (man lifts and snoopers) to prepare test patches in advance of the NDE technicians and thereby limit cleaning-related delays in the testing.

2.2.1 Initial Field Testing and Discovery of Cracked Splice Plates

At the onset of the NDE field work, KTC investigators visited the jobsite on September 30, 2008. Intech had established long-term traffic control on downstream curb lane of the Westbound Bridge and the upstream curb lane of the Eastbound Bridge. The traffic control consisted of placing reflective yellow stripes along the curb lanes and using plastic barrels to delineate the lane closure (Figure 17). Traffic was maintained along two of the three normal travel lanes. The traffic lane adjacent to the truss being inspected was closed to provide sufficient workspace for the access vehicles (snoopers and man-lifts). The lane closures were maintained over the entire length of the truss. Barrels were used to taper the lane closures starting at the entrance onto the side spans. Fixed signs and variable message boards were employed to alert motorists to the lane closures.

At that time, new Intech personnel were being trained to use vacuum shrouded grinders to prepare the steel for subsequent hardness testing (Figure 18).

The following day, HTT provided a technician and the supervisor at the jobsite. They both conducted hardness tests at the same sites and achieved good agreement in their test data. Work began on the lower chord of the downstream truss of Westbound Bridge on the Ohio end of the bridge. While that work was going on, personnel from a consulting firm were conducting an annual fracture-critical inspection of the bridges. During that work, they encountered a long crack in an A 514 steel splice plate on the upper chord of the downstream truss of the Eastbound Bridge at the central tower. The splice plate was located at the tower peak, inboard on the Ohio side of the truss.

On October 2, 2008, Intech shifted the lane-closure on the eastbound bridge to the downstream side of the bridge. On October 3, after obtaining a suitable (125-ft reach) man-lift, KTC and HTT personnel inspected the cracked splice plate. The crack had penetrated about halfway across the plate along a vertical line of bolts (Fig. 19). Testing with the *MIC 20* ultrasonic hardness tester provided inconsistent readings. Though the average of the readings was less than 30 HRC, there was extreme variability in obtaining the necessary 10 consistent readings required by the test protocol.

Later that day, the HTT supervisor came to the work site and used a *Telebrineller* to test the hardness on that plate. It provided consistent hardness values in the range of 40 HRC (converted from BHN using ASTM E 140-07) indicating that the cracked plate was made from the defective A 514 steel. After that, impact hardness testers were used to assess A 514 steel plates with ultrasonic hardness test values $\geq$ 25 HRC and the NDE technicians were cautioned to be alert to wide swings in ultrasonic hardness tests and to use the *Telebrineller* when extremely variable ultrasonic hardness values were obtained.

Immediately after that discovery, KYTC posted the eastbound bridge at 6,000 lb (e.g. limiting truck traffic to light pick-up trucks). KYTC also placed around-the-clock traffic enforcement on the approach of the eastbound bridge to prevent trucks (larger than pick-ups) from crossing it. The police oversight was charged to the KTC inspection project. Eventually, electronic signs on I 75 and I 275 notified truckers of the posting and provided detour information. The posting along with detour information was also announced by local media including television, radio and newspapers.

On October 3, KYTC officials came to the work site to inspect the cracked splice plate in the afternoon. They said that the posting was sufficient for the situation as it currently existed. They stated that testing work would continue.

In the second week of testing, the Mistras NDE technicians arrived at the IMR office in Louisville. The HTT supervisor provided them the *MIC 10* and *MIC 20* hardness testers with a number of 10 and 20 kgf probes. The *MIC 10* units operated identically to the *MIC 20s*, but were simpler with fewer test options. They were told about the test requirements and the necessity/importance of their work. The technicians were provided with a review of ultrasonic hardness testing principles. They were familiarized with the bridge plans and nomenclature. They were also apprised of the test protocol they would use on the bridges. In the afternoon, they were taught how to use their test instruments (Figure 20). Before being qualified for the bridge testing work, they had to successfully operate the ultrasonic hardness testers on steel in both the horizontal and vertical positions (Reference Figure 11).

Field testing with the 10 kgf probes eventually showed that they did not function properly on the A 514 steel and they were subsequently replaced with the 20 kgf probes. Those applied more contact force to the probe's sensing unit allowing it to penetrate deeper into the steel and provide more consistent hardness readings than the 10 kgf probes. After several days on site, the *MIC 10* units were found to be problematic and they were replaced with *MIC 20* units as soon as those could be acquired. The *MIC 20* testers used on the project were somewhat temperamental and experienced occasional breakdowns. Similarly the 20 kgf probes and cables were also subject to failure and frequently needed repairs/ replacement. To accommodate those issues, KTC sought to maintain a complete functioning spare *MIC 20* unit along with a signal cable and probe on-site at all times so equipment problems would not result in down time for the NDE technicians and their access equipment/operators.

The Mistras NDE technicians began work at the bridge on October 7, 2008 after receiving their training. At that point additional access equipment and operators were available. Several hours were spent familiarizing the technicians with interpreting the bridge plans. The HTT NDE inspector showed them how to perform the daily calibration procedure with the *MIC 20*.

After several days of testing, two of the NDE technicians were subsequently asked to test the remaining 1/2” external chord splice plates at the central tower (U16) locations on the eastbound and westbound downstream trusses. On October 14, one of the Mistras technicians detected a second cracked 1/2” external splice plate on the eastbound downstream truss diagonally across from the location of the first cracked splice plate. That plate was found to be brittle as were the other three 1/2” external splice plates at that location. Conversely all of the 1/2” external splice plates at U16 on the westbound bridge were found to conform to the specified steel hardness.

KYTC officials returned to bridges and inspected the second external cracked splice plate. Due to structural redundancy at that location, they decided to keep the bridge open (with the 6,000 lb posting). KYTC officials and KTC investigators discussed the possibility of conducting ultrasonic shear wave testing of the U16 splice plates on both downstream trusses and the eventual shifting of the lane closures to the upstream trusses to permit those tests of the similar splice plates at U16 locations on the upstream trusses. Since the eastbound downstream bridge was known to contain four external splice plates with out-of-spec. A 514 steel (two of which were cracked) and since the residual capacity of the joints in that area were sufficient with the bridge posting, the decision was made to forego ultrasonic shear wave testing at that location.

Shortly after that meeting, KYTC and ODOT officials held a conference call with KTC investigators concerning the status of the splice plates at the U16 locations. The decision was to perform ultrasonic shear wave tests on the U16 splice plates on the westbound downstream truss and immediately thereafter shift the lane closures back to the upstream trusses on both bridges to allow ultrasonic shear wave and hardness testing on the U 16 external splice plates on the upstream trusses.

KTC investigators discussed performing this work with the HTT NDE supervisor. He requested paint removal from the splice plates to permit ultrasonic testing. This was performed by Intech personnel using narrow belt sanders that enabled cleaning around the bolt heads on the splice plates.

On October 19, Intech shifted the lane closure on the eastbound bridge from the downstream truss to the upstream truss. The HTT NDE supervisor prepared a special defect calibration block to use with the ultrasonic shear wave testing (Figure 21). On

October 20 he performed that test along with the *Telebrineller* hardness tests on the four external splice plates at U16 on the downstream truss of the westbound bridge (Figure 22). That evening, Intech shifted the lane closure on the westbound bridge from the downstream truss to the upstream truss. On October 21 an HTT NDE technician performed the ultrasonic shear wave and *Telebrineller* tests on the U16 external splice plates on the westbound and eastbound upstream trusses. The ultrasonic shear wave testing did not find any additional cracks in the external splice plates. Hardness testing revealed two out-of-spec. external splice plates on the westbound upstream truss and one on the eastbound upstream truss.

2.2.2 Field Testing to Project Completion

As HTT conducted testing on the external splice plates at the U16 locations on the upstream trusses, the NDE technicians assigned to hardness testing began their work at other locations along the upstream trusses. The plan was to complete testing on the upstream trusses and subsequently move back to the downstream trusses that had been partially tested.

As the work had progressed on the downstream trusses, the NDE technicians occasionally encountered A 514 plates with hardness values below the minimum values specified for A 514 steel (below 235 brinell hardness number-BHN or ~21 HRC), but too high to indicate other types of steel. At first, this was considered a curiosity, but as the number of such findings rose, it became a concern (i.e., under-strength steel). IMR sent technicians to take surface replicas of the steel micro-structure on a piece exhibiting low strength (~200 BHN-Figure 23). The resulting replica indicated a mixed ferritic-fine carbide microstructure not the expected full martensitic microstructure. The decision was made to cut a coupon from the plate for laboratory evaluation (Figure 24). The cross-section of the coupon was polished, etched and subsequently examined using an optical microscope (Figure 25). Inspection revealed a thin decarburized surface ferritic-fine carbide surface layer over a martensitic core. That probably occurred during heat treatment. IMR and KTC investigators decided that the plates providing low hardness values were probably similar and that the low hardness values were due to surface effects. IMR subsequently conducted hardness tests on the interior martensite and found it to be within the specified hardness (9). The decision was made to accept all A 514 steel with similar hardness values as they probably were decarburized as well during tempering.

The testing progressed across the upstream trusses. Intech provided several personnel who could climb safely to access the interior portions of the upper chord box members to test internal splice plates. Problems were continually encountered with the reliability of the ultrasonic hardness testers and the access equipment (man-lifts and snoopers). Those had a minor impact on progress of the project.

At the request of KYTC, KTC investigators began providing work progress reports on a weekly basis several weeks after the field testing began. KTC investigators initially provided the NDE technicians with paper test forms to track the test sites inspected and the test results. Eventually, to expedite the work, the progress was tracked using spreadsheets e-mailed by several technicians who had laptop computers. Typically, they summarized tests conducted during the work week and e-mailed those to KTC on the weekend for transmittal to KYTC early the following week.

The anticipated pace of testing had been hindered by discoveries of the cracked splice plates and subsequent efforts to properly address that issue. KYTC officials pressed KTC to complete the work by the end of November. KTC investigators sought to obtain more NDE personnel, but none were available locally and Mistras sought to find other qualified personnel on a national basis. The ultrasonic test equipment was equally difficult to obtain. These shortages were attributable to annual plant closures for maintenance and inspection that were prevalent in the petroleum, power and chemical industries. Those usually occurred in the fall-early winter. As the work progressed, there were typically 4-5 NDE technicians working with two on man-lifts and the others using snoopers. Additional man-lifts were on site to allow Intech personnel to clean test sites ahead of the NDE technicians. On some occasions, the NDE technicians went to Louisville to address office issues with Mistras while the Intech personnel cleaned new test patches and painted over completed ones. There were continual problems with the access equipment (man-lifts and snoopers) and, as the work progressed, several spare man-lifts were kept on the project to minimize downtime when working units broke down.

In addition to the initial NDE testing, the NDE technicians were asked to periodically check each other's work, or if circumstances required, recheck their own work for ultrasonic tests providing hardness values ≥ 25 HRC. Initially, KTC investigators planned to perform those quality assurance tests. However, due to the high workload entailed in project oversight and the limited availability of access vehicles/operators, the NDE technicians were assigned to perform those duties. Another quality assurance duty passed on to the technicians was to inspect all of the completed test patches and ensure that they had been properly labeled. A KTC investigator was given the duty of going over the NDE technicians' digital pictures of the test locations to assure that work was completed. Any found to be missing were identified and the NDE technicians were sent back to those locations to ensure they were properly tested, documented and photographed.

Eventually, Mistras was able to provide several additional technicians who were trained by IMR on November3. The following day, they were sent to the bridge and assigned to work with the other NDE technicians until they became familiar with their assigned tasks and with the bridge test nomenclature/locations. HTT took their NDE inspector off the job just prior to that and shortly thereafter one of the original Mistras technicians was reassigned to another project. On November 5, KYTC officials came to the work site and assisted the NDE technicians in testing sites that were difficult to access. The work continued routinely on the upstream trusses with a few lost days due to rain and a bomb threat on November 14.

The work on the eastbound upstream truss was completed on November 20. Intech subsequently shifted the lane closure back to the downstream truss. On November 23, work was completed on the westbound upstream and that lane closure was also moved back to the downstream truss. Testing on the downstream trusses had been partially completed previously and work was initiated on the untested pieces as well as the quality assurance testing. All of the test patch areas previously cleaned had corroded and needed to be re-prepared by grinding. The work progressed satisfactorily and all testing was completed for both downstream trusses on December 5, 2010. Prior to the end of the field testing, KTC investigators went over all of the test data and reviewed all the test location pictures to ensure the work was complete.

Once the testing was completed, Intech removed the lane closures (i.e., traffic barrels and temporary stripes) and left the work site to demobilize. The Mistras NDE technicians returned to the Louisville office and returned all of the test equipment and their test logs. The latter were reviewed by the HTT NDE supervisor at that time. KTC retained the test data, inspector logs and test site pictures for future reference. At that point, the field testing was officially completed.

2.3 POST-TEST WORK ADDRESSING DEFECTIVE STEEL

KTC and IMR investigators subsequently reviewed the test results and summarized them for KYTC officials (10). Thereafter, until all the defective steel was removed or reinforced, KYTC personnel conducted monthly “arm’s length” inspections on those pieces to ensure they remained intact. No additional cracking was observed in the defective steel plates during those inspections.

In mid-December 2008, KYTC contracted with Intech to remove defective external splice plates on the eastbound bridge at the tower (U16) locations. Those were removed at night on weekends to minimize motorist inconvenience on the heavily traveled bridge. The plates were secured by KTC and taken to IMR for follow-on testing and storage. After those plates were removed, the posting and traffic control were removed from the eastbound bridge. During the field testing, Intech had reviewed the re-painting of test patches on each truss. At the end of the normal field work, Apex personnel detected several test patch locations on the eastbound bridge trusses that were not repainted. Those locations were provided to Intech for repainting during the plate replacement work.

In 2009 URS Corporation was awarded a design contract for retrofits of several plates that could not be readily replaced. These included two 3/4” horizontal gusset plates at L16 on the eastbound and westbound bridge upstream trusses.
The other was a 1/2” internal inboard splice plate at L2’ on the westbound bridge upstream truss. Those plates were reinforced with lapping plates, fastening them with high-strength bolts.

Kay and Kay Contracting Inc. was subsequently awarded a contract to remove the balance of the defective A 514 steel. As before, this work was performed on weekends at night beginning in January 2010 with the last work being completed on the first week of June 2010. KTC received all of the defective steel that was replaced. Corner coupons were taken from the defective A 514 plates that were lapped. KTC took all of the defective plates/coupons to IMR for testing and subsequent storage (except for the horizontal gusset plate coupons that were extracted by IMR).

A timeline for this entire event from initial detection of cracked plates to final laboratory evaluation of removed defective material is provided in Table 5. The total project cost including KTC work was $1,981,138.

3. SUMMARY OF TEST RESULTS

During the field NDE testing, 1,356 plates were tested (including those comprising the box chord members). Tests were performed at over 3,000 locations as part of both the initial and follow-up QA testing. Those tests involved about 30,000 measurements as each ultrasonic test was comprised of the average of at least 10 corresponding readings (generally within ±3 HRC).

In addition to the three 3/8” splice plates originally removed in early 2008, the NDE work performed under this project detected an additional 14 plates made from defective A 514 steel. As previously noted, two of those plates had begun to experience cracking as the project commenced. The defective steel plates/locations are provided in Table 4. All of the steel plates were taken to IMR for bench hardness testing to confirm whether or not the plates were defective (out-of-spec.). All 14 pieces of A 514 steel identified by the field tests as being out-of-spec./defective were confirmed to be so by the IMR laboratory bench hardness tests (Appendix B).

IMR conducted additional evaluations of the two cracked 1/2” splice plates from the downstream tower of the eastbound bridge. Unlike the cracked lower chord 3/8” splice plates on the westbound bridge, the two cracked 1/2” splice plates did not exhibit signs of SCC/HSC. However, signs of corrosion fatigue were present. That was probably due to the fact that the concentration of corrodants such as chlorides was lower at the tower locations. IMR summarized all of its work in a final report (11).

4. CONCLUSIONS

The KTC NDE field tests were identified all of the out-of-spec./defective A 514 steel on the bridges. Testing by IMR confirmed that all of the plates designated by KTC field NDE tests as being defective were so. Considering the high number of initial tests and back-up QA tests, it is highly unlikely that the KTC field NDE tests provided any misses. At this juncture, the NDE field test project appears to have been entirely successful.

The steel furnished to ASTM A 514 did not meet that specification due to mechanical properties, not chemical composition. The ASTM A 514 specification does not address the microstructure of the steel that is affected by thermal processing (i.e. quenching and tempering). For some reason, the steel supplier did not properly temper 17 plates used in the bridge. Fortunately the number of out-of-spec. plates was low and those were not in fracture-critical applications. The fact that A 514 plates were found with surface decarburization attests to the notion that the steel manufacturer had issues with its process controls. The cracking of 5 of the 17 plates with the out-of-spec. steel indicates how defective the material was. Several of those exhibited SCC/HSC which is not anticipated in ASTM A 514 steel (12). All of the cracked plates were splice plates which have no welding and are usually not associated with any fracture mechanism. The inadequacy of these plates is indicated by the fact that none of the 1,339 plates of acceptable A 514 steel, including those that were welded, showed any signs of cracking. The out-of-spec. plates were defective both in required mechanical properties and in actual field performance.

During this project, it was determined that some of the filler plates used in conjunction with the lower chord splice plates did not have the same thickness as the gusset plates to which they were attached. That deformed the splice plates and probably contributed to cracking in the 3/8” lower chord splice plates. The NDE technicians were asked to check the filler plate thicknesses, but did not do that consistently. Subsequently, a consultant conducting inspection work on the bridge performed those measurements on the lower chords of the bridge. In some cases, no/little variation was observed between the thicknesses of the filler and gusset plates. In other cases, the variability was up to 0.1”. That was in general agreement with IMR findings of a permanent offset in the face of one cracked 3/8” splice plate (13). The differences in thicknesses between the filler plates and gussets may have contributed to the fracturing of the out-of-spec./defective splice plates, but only because the steel was defective. Other lower chord splice plates at similar locations that were made of acceptable A 514 steel did not crack.

5. RECOMMENDATIONS

The following *recommendations* are provided:

1. KYTC has funded a related SPR study, KYSPR 09-401 “Kentucky Bridges with High Strength Quenched and Tempered Steel.” The purpose of that study is to identify other KYTC bridges with QT steel in case similar problems should arise on those bridges. *KYTC should retain a list of those bridges and conduct hardness tests on the QT steel if cracking problems are ever detected.*
2. On this project, the NDE testing appears to have been effective in discriminating between acceptable and defective A 514 steel. However, with any NDE testing, some caution is always advisable in moving forward. *In about 5 years, KYTC should conduct an “arms length” inspection of all A 514 steel on the I-275 Combs-Hehl Bridges and repeat that type of inspection every 5 years thereafter.*

6. REFERENCES

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7. TABLES

Table 1. Chemical Composition (%) of Cracked ASTM A 514 Splice Plates Compared to ASTM A 514 Gr. B Steel.				
Element	Cracked Plate 1	Cracked Plate 2	Cracked Plate 3	ASTM Specification
Carbon	0.21	0.21	0.21	0.12 – 0.21
Silicon	0.28	0.29	0.29	0.20 – 0.35
Manganese	0.88	0.90	0.88	0.70 – 1.00
Phosphorus	0.008	0.008	0.007	0.035 max
Sulfur	0.022	0.021	0.022	0.035 max
Chromium	0.52	0.53	0.52	0.40 - 0.65
Molybdenum	0.17	0.17	0.17	0.15 – 0.25
Nickel	0.05	0.05	0.05	------
Aluminum	0.035	0.034	0.035	------
Cobalt	< 0.01	< 0.01	< 0.01	------
Copper	0.02	0.02	0.02	------
Niobium	< 0.01	< 0.01	< 0.01	------
Titanium	0.02	0.02	0.02	0.01 – 0.03
Vanadium	0.05	0.05	0.05	0.03 – 0.08
Tungsten	< 0.01	< 0.01	< 0.01	------
Lead	< 0.01	< 0.01	< 0.01	------
Boron	0.0016	0.0017	0.0014	0.0005 – 0.005
Iron	Remainder	Remainder	Remainder	Remainder

Table 2. Mechanical Properties of Cracked Plates Compared to Those Specified for ASTM A 514				
Sample	Tensile Strength (ksi)	0.2% Yield Strength (ksi)	Elongation in 2" (%)	Hardness (HRC)
Cracked Plate 1	192.7	177.1	13	42
Cracked Plate 2	199.6	178.2	13	40
Cracked Plate 3	195.0	178.6	13	41
ASTM A 514 Spec.	110 - 130	100 min.	18 min.	~21-31

Table 3. Test Locations for ASTM A 514 Steel on Trusses of I-275 Combs-Hehl Twin Bridges					
Test No.	Location	Member	Plates	Cover Plates	Splice Plates
			Size	Size	Size
	Lower Chord	L0-L2			
1	Lower Chord	L2-L4 Inboard	1 1/16 x 31		
2	Lower Chord	L2-L4 Outboard	1 1/16 x 31		
3	Lower Chord	L2-L4 Top		½ x 22½	
4	Lower Chord	L2-L4 Bottom		½ x 22½	
5	Lower Chord	L4-L6 Inboard	1⅜ x 31		
6	Lower Chord	L4-L6 Outboard	1⅜ x 31		
7	Lower Chord	L4-L6 Top		½ x 22½	
8	Lower Chord	L4-L6 Bottom		½ x 22½	
9	Lower Chord	L6-L8 Inboard	1 3/16 x 31		
10	Lower Chord	L6-L8 Outboard	1 3/16 x 31		
11	Lower Chord	L6-L8 Top		½ x 22½	
12	Lower Chord	L6-L8 Bottom		½ x 22½	
13	Lower Chord	L8-L10 Inboard	¾ x 31		
14	Lower Chord	L8-L10 Outboard	¾ x 31		
15	Lower Chord	L8-L10 Top		½ x 23	
16	Lower Chord	L8-L10 Bottom		½ x 23	
	Lower Chord	L10-L12			
17	Lower Chord	L12-L14 Inboard	1½ x 31		
18	Lower Chord	L12-L14 Outboard	1½ x 31		
19	Lower Chord	L12-L14 Top		¾ x 22½	
20	Lower Chord	L12-L14 Bottom		¾ x 22½	
21	Lower Chord	L14-L16 Inboard	1½ x 31		

22	Lower Chord	L14-L16 Outboard	1½ x 31		
23	Lower Chord	L14-L16 Top		¾ x 22½	
24	Lower Chord	L14-L16 Bottom		¾ x 22½	
25	Lower Chord	L14’-L16’ Inboard	1½ x 31		
26	Lower Chord	L14’-L16’ Outboard	1½ x 31		
27	Lower Chord	L14’-L16’ Top		¾ x 22½	
28	Lower Chord	L14’-L16’ Bottom		¾ x 22½	
29	Lower Chord	L12’-L14’ Inboard	1½ x 31		
30	Lower Chord	L12’-L14’ Outboard	1½ x 31		
31	Lower Chord	L12’-L14’ Top		¾ x 22½	
32	Lower Chord	L12’-L14’ Bottom		¾ x 22½	
	Lower Chord	L10’-L12’			
33	Lower Chord	L8’-L10’ Inboard	¾ x 31		
34	Lower Chord	L8’-L10’ Outboard	¾ x 31		
35	Lower Chord	L8’-L10’ Top		½ x 23	
36	Lower Chord	L8’-L10’ Bottom		½ x 23	
37	Lower Chord	L6’-L8’ Inboard	1 3/16 x 31		
38	Lower Chord	L6’-L8’ Outboard	1 3/16 x 31		
39	Lower Chord	L6’-L8’ Top		½ x 22½	
40	Lower Chord	L6’-L8’ Bottom		½ x 22½	
41	Lower Chord	L4’-L6’ Inboard	1⅜ x 31		
42	Lower Chord	L4’-L6’ Outboard	1⅜ x 31		
43	Lower Chord	L4’-L6’ Top		½ x 22½	
44	Lower Chord	L4’-L6’ Bottom		½ x 22½	
45	Lower Chord	L2’-L4’ Inboard	1 1/16 x 31		
46	Lower Chord	L2’-L4’ Outboard	1 1/16 x 31		

47	Lower Chord	L2’-L4’ Top		½ x 22½	
48	Lower Chord	L2’-L4’ Bottom		½ x 22½	
	Lower Chord	L0’-L2’			
	Upper Chord	L0-U1			
	Upper Chord	U1-U3			
49	Upper Chord	U3-U5 Inboard	1½ x 31		
50	Upper Chord	U3-U5 Outboard	1½ x 31		
51	Upper Chord	U3-U5 Top		¾ x 22½	
52	Upper Chord	U3-U5 Bottom		¾ x 22½	
53	Upper Chord	U5-U7 Inboard	1½ x 31		
54	Upper Chord	U5-U7 Outboard	1½ x 31		
55	Upper Chord	U5-U7 Top		¾ x 22½	
56	Upper Chord	U5-U7 Bottom		¾ x 22½	
57	Upper Chord	U7-U9 Inboard	1⅜ x 31		
58	Upper Chord	U7-U9 Outboard	1⅜ x 31		
59	Upper Chord	U7-U9 Top		¾ x 22½	
60	Upper Chord	U7-U9 Bottom		¾ x 22½	
	Upper Chord	U9-U11			
	Upper Chord	U11-U13			
	Upper Chord	U13-U14			
61	Upper Chord	U14-U16 Inboard	2¼ x 31		
62	Upper Chord	U14-U16 Outboard	2¼ x 31		
63	Upper Chord	U14-U16 Top		½ x 22½	
64	Upper Chord	U14-U16 Bottom		½ x 22½	
65	Upper Chord	U14’-U16’ Inboard	2¼ x 31		
66	Upper Chord	U14’-U16’ Outboard	2¼ x 31		

67	Upper Chord	U14’-U16’ Top		½ x 22½	
68	Upper Chord	U14’-U16’ Bottom		½ x 22½	
	Upper Chord	U13’-U14’			
	Upper Chord	U11’-U13’			
	Upper Chord	U9’-U11’			
69	Upper Chord	U7’-U9’ Inboard	1⅜ x 31		
70	Upper Chord	U7’-U9’ Outboard	1⅜ x 31		
71	Upper Chord	U7’-U9’ Top		¾ x 22½	
72	Upper Chord	U7’-U9’ Bottom		¾ x 22½	
73	Upper Chord	U5’-U7’ Inboard	1½ x 31		
74	Upper Chord	U5’-U7’ Outboard	1½ x 31		
75	Upper Chord	U5’-U7’ Top		¾ x 22½	
76	Upper Chord	U5’-U7’ Bottom		¾ x 22½	
77	Upper Chord	U3’-U5’ Inboard	1½ x 31		
78	Upper Chord	U3’-U5’ Outboard	1½ x 31		
79	Upper Chord	U3’-U5’ Top		¾ x 22½	
80	Upper Chord	U3’-U5’ Bottom		¾ x 22½	
	Upper Chord	L0’-U1’			
	Diagonal	U1-L2			
	Diagonal	L2-U3			
	Diagonal	U3-L4			
	Diagonal	L4-U5			
	Diagonal	U5-L6			
	Diagonal	L6-U7			
	Diagonal	U7-L8			
	Diagonal	L8-U9			

	Diagonal	U9-L10			
	Diagonal	L10-U11			
	Diagonal	U11-L12			
81	Diagonal	L12-M13 Inboard	1⅛ x 31		
82	Diagonal	L12-M13 Outboard	1⅛ x 31		
83	Diagonal	L12-M13 Top		½ x 22½	
84	Diagonal	L12-M13 Bottom		½ x 22½	
85	Diagonal	M13-U14 Inboard	1½ x 31	½ x 22½	
86	Diagonal	M13-U14 Outboard	1½ x 31		
87	Diagonal	M13-U14 Top		½ x 22½	
88	Diagonal	M13-U14 Bottom		½ x 22½	
89	Diagonal	U14-M15 Inboard	1½ x 31		
90	Diagonal	U14-M15 Outboard	1½ x 31		
91	Diagonal	U14-M15 Top		¾ x 22½	
92	Diagonal	U14-M15 Bottom		¾ x 22½	
93	Diagonal	M15-L16 Inboard	1 11/16 x 31		
94	Diagonal	M15-L16 Outboard	1 11/16 x 31		
95	Diagonal	M15-L16 Top		¾ x 22½	
96	Diagonal	M15-L16 Bottom		¾ x 22½	
97	Diagonal	M15’-L16’ Inboard	1 11/16 x 31		
98	Diagonal	M15’-L16’ Outboard	1 11/16 x 31		
99	Diagonal	M15’-L16’ Top		¾ x 22½	
100	Diagonal	M15’-L16’ Bottom		¾ x 22½	
101	Diagonal	U14’-M15’ Inboard	1½ x 31		
102	Diagonal	U14’-M15’ Outboard	1½ x 31		
103	Diagonal	U14’-M15’ Top		¾ x 22½	

104	Diagonal	U14’-M15’ Bottom		¾ x 22½	
105	Diagonal	M13’-U14’ Inboard	1½ x 31		
106	Diagonal	M13’-U14’ Outboard	1½ x 31		
107	Diagonal	M13’-U14’ Top		½ x 22½	
108	Diagonal	M13’-U14’ Bottom		½ x 22½	
109	Diagonal	L12’-M13’ Inboard	1⅛ x 31		
110	Diagonal	L12’-M13’ Outboard	1⅛ x 31		
111	Diagonal	L12’-M13’ Top		½ x 22½	
112	Diagonal	L12’-M13’ Bottom		½ x 22½	
	Diagonal	U11’-L12’			
	Diagonal	L10’-U11’			
	Diagonal	U9’-L10’			
	Diagonal	U7’-L8’			
	Diagonal	L6’-U7’			
	Diagonal	U5’-L6’			
	Diagonal	L4’-U5’			
	Diagonal	L2’-U3’			
	Diagonal	U1’-L2’			
	Sub-diagonal	M13-L14			
	Sub-diagonal	L14-M15			
	Sub-diagonal	L14’-M15’			
	Sub-diagonal	M13’-L14’			
	Hanger	U1-L1			
	Hanger	U3-L3			
	Hanger	U5-L5			
	Hanger	U7-L7			

	Hanger	U9-L9			
	Hanger	U11-L11			
	Hanger	M13-L13			
	Hanger	U14-L14			
	Hanger	M15-L15			
	Hanger	M15'-L15'			
	Hanger	U14'-L14'			
	Hanger	M13'-L13'			
	Hanger	U11'-L11'			
	Hanger	U9'-L9'			
	Hanger	U7'-L7'			
	Hanger	U5'-L5'			
	Hanger	U3'-L3'			
	Hanger	U1'-L1'			
	Post	U2-L2			
	Post	U4-L4			
	Post	U6-L6			
	Post	U8-L8			
	Post	U10-L10			
	Post	U12-L12			
	Post	U13-M13			
	Post	U15-M15			
113	Post	U16-M16 Inboard	1¼ x 28½		
114	Post	U16-M16 Outboard	1¼ x 28½		
115	Post	U16-M16 KY		13/16 x 22 1/2	
116	Post	U16-M16 OH		13/16 x 22 1/2	

117	Post	M16-L16 Inboard	1⅜ x 28½		
118	Post	M16-L16 Outboard	1⅜ x 28½		
119	Post	M16-L16 Top			
120	Post	M16-L16 Bottom			
	Post	U15’-M15’			
	Post	U13’-M13’			
	Post	U12’-L12’			
	Post	U10’-L10’			
	Post	U8’-L8’			
	Post	U6’-L6’			
	Post	U4’-L4’			
	Post	U2’-L2’			
	Strut	M15-M16			
	Strut	M15’-M16’			
	Joint	L0			
	Joint	L1			
121	Joint	L2 Inboard	¾		
122	Joint	L2 Outboard	¾		
123	Joint	L2 Internal Inboard			½ x 30
124	Joint	L2 Internal Outboard			½ x 30
125	Joint	L2 Top			7/16 x 21
126	Joint	L2 Bottom			9/16 x 17
	Joint	L3			
127	Joint	L4 Inboard	¾		
128	Joint	L4 Outboard	¾		
129	Joint	L4 Internal Inboard			¾ x 30

130	Joint	L4 Internal Outboard			¾ x 30
131	Joint	L4 Top			7/16 x 21
132	Joint	L4 Bottom			7/16 x 17
	Joint	L5			
133	Joint	L6 Inboard	¾		
134	Joint	L6 Outboard	¾		
135	Joint	L6 Internal Inboard			1½ x 30
136	Joint	L6 Internal Outboard			1½ x 30
137	Joint	L6 Top			7/16 x 21
138	Joint	L6 Bottom			7/16 x 17
	Joint	L7			
139	Joint	L8 Inboard	¾		
140	Joint	L8 Outboard	¾		
141	Joint	L8 Internal Inboard			¾ x 30
142	Joint	L8 Internal Outboard			¾ x 30
143	Joint	L8 Top			7/16 x 21
144	Joint	L8 Bottom			9/16 x 17
	Joint	L9			
145	Joint	L10 Inboard	¾		
146	Joint	L10 Outboard	¾		
147	Joint	L10 Top			7/16 x 21
148	Joint	L10 Bottom			9/16 x 17
	Joint	L11			
149	Joint	L12 Inboard	¾		
150	Joint	L12 Outboard	¾		
151	Joint	L12 Inboard Splice			⅜ x 31

152	Joint	L12 Outboard Splice			⅜ x 31
153	Joint	L12 Top			⅜ x 21
154	Joint	L12 Bottom			7/16 x 17
	Joint	L13			
155	Joint	L14 Inboard	¾		
156	Joint	L14 Outboard	¾		
157	Joint	L14 Internal Inboard			¾ x 30
158	Joint	L14 Internal Outboard			¾ x 30
159	Joint	L14 Top			⅜ x 21
160	Joint	L14 Bottom			7/16 x 17
161	Joint	L15 Inner Inboard			
162	Joint	L15 Outer Inboard	½		
163	Joint	L15 Inner Outboard			
164	Joint	L15 Outer Outboard	½		
165	Joint	L16 Inner Inboard	⅞		
166	Joint	L16 Outer Inboard	⅞		
167	Joint	L16 Inner Outboard	⅞		
168	Joint	L16 Outer Outboard	⅞		
169	Joint	L16 Inboard Horiz. Splice OH Side			½ x 31
170	Joint	L16 Outboard Horiz. Splice OH Side			½ x 31
171	Joint	L16 Inboard Horiz. Splice KY Side			½ x 31
172	Joint	L16 Outboard Horiz. Splice KY Side			½ x 31
173	Joint	L16 Inboard Diag. Splice OH Side			¾ x 31
174	Joint	L16 Outboard Diag. Splice OH Side			¾ x 31
175	Joint	L16 Inboard Diag. Splice KY Side			¾ x 31

176	Joint	L16 Outboard Diag. Splice KY Side			¾ x 31
177	Joint	L16 Horizontal Gusset	¾		
178	Joint	L16 Internal Plate See Sht. 13	¾ x 24 x 28½		
179	Joint	L16 Vertical Plate See Sht. 13	1⅝ x 20¾ x 110		
180	Joint	L15' Inner Inboard			
181	Joint	L15' Outer Inboard	½		
182	Joint	L15' Inner Outboard			
183	Joint	L15' Outer Outboard	½		
184	Joint	L14' Inboard	¾		
185	Joint	L14' Outboard	¾		
186	Joint	L14' Internal Inboard			¾ x 30
187	Joint	L14' Internal Outboard			¾ x 30
188	Joint	L14' Top			⅜ x 21
189	Joint	L14' Bottom			7/16 x 17
190	Joint	L13'			
191	Joint	L12' Inboard	¾		
192	Joint	L12' Outboard	¾		
193	Joint	L12' Inboard Splice			⅜ x 31
194	Joint	L12' Outboard Splice			⅜ x 31
195	Joint	L12' Top			⅜ x 21
196	Joint	L12' Bottom			7/16 x 17
197	Joint	L11			
198	Joint	L10' Bottom			7/16 x 17
199	Joint	L10' Top			7/16 x 21
200	Joint	L10' Inboard	¾		
201	Joint	L10' Outboard	¾		

202	Joint	L9			
203	Joint	L8’ Bottom			7/16 x 17
204	Joint	L8’ Top			7/16 x 21
205	Joint	L8’ Inboard	¾		
206	Joint	L8’ Outboard	¾		
207	Joint	L8’ Internal Inboard			¾ x 30
208	Joint	L8’ Internal Outboard			¾ x 30
	Joint	L7’			
209	Joint	L6’ Bottom			7/16 x 17
210	Joint	L6’ Top			7/16 x 21
211	Joint	L6’ Inboard	¾		
212	Joint	L6’ Outboard	¾		
213	Joint	L6’ Internal Inboard			¾ x 30
214	Joint	L6’ Internal Outboard			¾ x 30
	Joint	L5’			
215	Joint	L4’ Bottom			7/16 x 17
216	Joint	L4’ Top			7/16 x 21
217	Joint	L4’ Inboard	¾		
218	Joint	L4’ Outboard	¾		
219	Joint	L4’ Internal Inboard			¾ x 30
220	Joint	L4’ Internal Outboard			¾ x 30
	Joint	L3’			
221	Joint	L2’ Bottom			9/16 x 17
222	Joint	L2’ Top			7/16 x 21
223	Joint	L2’ Inboard	¾		
224	Joint	L2’ Outboard	¾		

225	Joint	L2' Internal Inboard			½ x 30
226	Joint	L2' Internal Outboard			½ x 30
	Joint	L1'			
	Joint	L0'			
	Joint	U1			
	Joint	U2			
227	Joint	U3 Inboard	¾		
228	Joint	U3 Outboard	¾		
229	Joint	U3 Internal Inboard			½ x 30
230	Joint	U3 Internal Outboard			½ x 30
231	Joint	U3 Bottom			⅜ x 21
232	Joint	U3 Top			7/16 x 17
	Joint	U4			
233	Joint	U5 Inboard	¾		
234	Joint	U5 Outboard	¾		
235	Joint	U5 Internal Inboard			¾ x 30
236	Joint	U5 Internal Outboard			¾ x 30
237	Joint	U5 Bottom			⅜ x 21 *
238	Joint	U5 Top			7/16 x 17 *
	Joint	U6			
239	Joint	U7 Inboard	¾		
240	Joint	U7 Outboard	¾		
241	Joint	U7 Internal Inboard			½ x 30
242	Joint	U7 Internal Outboard			½ x 30
243	Joint	U7 Bottom			⅜ x 21
244	Joint	U7 Top			7/16 x 17

	Joint	U8			
245	Joint	U9 Inboard	¾		
246	Joint	U9 Outboard	¾		
247	Joint	U9 Bottom			⅜ x 21 *
248	Joint	U9 Top			7/16 x 17 *
	Joint	U10			
249	Joint	U11 Inboard	¾		
250	Joint	U11 Outboard	¾		
	Joint	U12			
	Joint	U13			
251	Joint	U14 Inner Inboard	¾		
252	Joint	U14 Outer Inboard	¾		
253	Joint	U14 Inner Outboard	¾		
254	Joint	U14 Outer Outboard	¾		
255	Joint	U14 OH Upper Chord Splice Inboard			⅝ x 31
256	Joint	U14 OH Upper Chord Splice Outb'd			⅝ x 31
257	Joint	U14 Internal Inboard			⅞ x 30
258	Joint	U14 Internal Outboard			⅞ x 30
259	Joint	U14 Diag. Splice KY Inboard			¾ x 31
260	Joint	U14 Diag. Splice KY Outboard			¾ x 31
261	Joint	U14 Diag. Splice OH Inboard			¾ x 31
262	Joint	U14 Diag. Splice OH Outboard			¾ x 31
263	Joint	U14 Bottom			7/16 x 21 *
264	Joint	U14 Top			9/16 x 17 *

	Joint	U15			
265	Joint	U16 Inner Inboard	¾		
266	Joint	U16 Outer Inboard	¾		
267	Joint	U16 Inner Outboard	¾		
268	Joint	U16 Outer Outboard	¾		
269	Joint	U16 KY Internal Splice Inboard			1½ x30
270	Joint	U16 KY Internal Splice Outboard			1½ x30
271	Joint	U16 OH Internal Splice Inboard			1½ x30
272	Joint	U16 OH Internal Splice Outboard			1½ x30
273	Joint	U16 KY External Splice Inboard			½ x 31
274	Joint	U16 KY External Splice Outboard			½ x 31
275	Joint	U16 OH External Splice Inboard			½ x 31
276	Joint	U16 OH External Splice Outboard			½ x 31
277	Joint	U16 Bottom			7/16 x 19 *
278	Joint	U16 Top			7/16 x 19 *
	Joint	U15’			
279	Joint	U14’ Inner Inboard	¾		
280	Joint	U14’ Outer Inboard	¾		
281	Joint	U14’ Inner Outboard	¾		
282	Joint	U14’ Outer Outboard	¾		
283	Joint	U14’ OH Upper Chord Splice Inboard			⅝ x 31
284	Joint	U14’ OH Upper Chord Splice Outb’d			⅝ x 31
285	Joint	U14’ Internal Inboard			⅞ x 30
286	Joint	U14’ Internal Outboard			⅞ x 30

287	Joint	U14’ Diag. Splice KY Inboard			¾ x 31
288	Joint	U14’ Diag. Splice KY Outboard			¾ x 31
289	Joint	U14’ Diag. Splice OH Inboard			¾ x 31
290	Joint	U14’ Diag. Splice OH Outboard			¾ x 31
291	Joint	U14’ Bottom			7/16 x 21 *
292	Joint	U14’ Top			9/16 x 17 *
	Joint	U13’			
	Joint	U12’			
293	Joint	U11’ Inboard	¾		
294	Joint	U11’ Outboard	¾		
	Joint	U10’			
295	Joint	U9’ Top			7/16 x 17
296	Joint	U9’ Bottom			⅜ x 21
297	Joint	U9’ Inboard	¾		
298	Joint	U9’ Outboard	¾		
	Joint	U8’			
299	Joint	U7’ Top			7/16 x 17
300	Joint	U7’ Bottom			⅜ x 21
301	Joint	U7’ Inboard	¾		
302	Joint	U7’ Outboard	¾		
303	Joint	U7’ Internal Inboard			½ x 30
304	Joint	U7’ Internal Outboard			½ x 30
	Joint	U6’			
305	Joint	U5’ Top			7/16 x 17
306	Joint	U5’ Bottom			⅜ x 21

307	Joint	U5’ Inboard	¾		
308	Joint	U5’ Outboard	¾		
309	Joint	U5’ Internal Inboard			½ x 30
310	Joint	U5’ Internal Outboard			½ x 30
	Joint	U4’			
311	Joint	U3’ Top			7/16 x 17
312	Joint	U3’ Bottom			⅜ x 21
313	Joint	U3’ Inboard	¾		
314	Joint	U3’ Outboard	¾		
315	Joint	U3’ Internal Inboard			½ x 30
316	Joint	U3’ Internal Outboard			½ x 30
	Joint	U2’			
	Joint	U1’			
317	Joint	M13 Inboard	¾		
318	Joint	M13 Outboard	¾		
319	Joint	M13 Internal Inboard			11/16x 30
320	Joint	M13 Internal Outboard			11/16x 30
321	Joint	M13 Top Splice of Diag.			½ x 21
322	Joint	M13 Bottom Splice of Diag???			½ x 21
323	Joint	M15 Inboard	⅝		
324	Joint	M15 Outboard	⅝		
325	Joint	M15 Internal Inboard			½ x 30
326	Joint	M15 Internal Outboard			½ x 30
327	Joint	M15 Top Splice of Diag.			⅜ x 21
328	Joint	M15 Bottom Splice of Diag???			⅜ x 21
329	Joint	M16 Internal Inboard			½ x 27½

330	Joint	M16 Internal Outboard			½ x 27½
331	Joint	M16 External Inboard			½ x 28½
332	Joint	M16 External Outboard			½ x 28½
333	Joint	M16 KY Face See Sht. 13			⅜ x 21
334	Joint	M16 OH Face See Sht. 13			⅜ x 21
335	Joint	M15' Top Splice of Diag.			⅜ x 21
336	Joint	M15' Bottom Splice of Diag???			⅜ x 21
337	Joint	M15' Inboard	⅝		
338	Joint	M15' Outboard	⅝		
339	Joint	M15' Internal Inboard			½ x 30
340	Joint	M15' Internal Outboard			½ x 30
341	Joint	M13' Top Splice of Diag.			½ x 21
342	Joint	M13' Bottom Splice of Diag.??			½ x 21
343	Joint	M13' Inboard	¾		
344	Joint	M13' Outboard	¾		
345	Joint	M13' Internal Inboard			11/16 x 30
346	Joint	M13' Internal Outboard			11/16 x 30

Table 4. Defective (Out-of-Specification) ASTM A 514 Steel Detected on the I-275 Combs-Hehl Bridges During KTC Field Testing (10-1-08 to 12-5-08) Defective ASTM A 514 Steel Hardness (HRC>32 and/or BHN>310			
Plate Number	Structure/ Truss	Plate Location/Description	Plate Hardness
151	Westbound/ Upstream	L12/External Inboard Splice Plate-3/8" Thick	37.3 to 37.4 HRC (Ultrasonic) 364 to 374 BHN (Telebrineller)
177	Westbound/ Upstream	L16/Horizontal Gusset Plate-3/4" Thick	30.3 to 31.2 HRC (Ultrasonic) 324to 334 BHN (Telebrineller)
225	Westbound/ Upstream	L2'/ Internal Inboard Splice Plate-1/2" Thick	350 to 383 BHN (Telebrineller)
273	Westbound/ Upstream	U 16/KY External Inboard Splice Plate-1/2" Thick	33.1 to 34.3 HRC (Ultrasonic) 364 BHN (Telebrineller)
274	Westbound/ Upstream	U 16/KY External Outboard Splice Plate-1/2" Thick	28.0 to 32.9 HRC (Ultrasonic) 355 (Telebrineller)
151	Westbound/ Downstream	L12/External Inboard Splice Plate-3/8" Thick	36.8 to 42.3 HRC (Ultrasonic) 365 to 384 BHN (Telebrineller)
152	Westbound/ Downstream	L12/External Outboard Splice Plate-3/8" Thick	33.4 to 36.0 HRC (Ultrasonic) 370 to 388 BHN (Telebrineller)
177	Eastbound/ Upstream	L16/Horizontal Gusset Plate-3/4" Thick	26.5 to 30.3 HRC (Ultrasonic) 311 to 315 BHN (Telebrineller)
274	Eastbound/ Upstream	U 16/KY External Outboard Splice Plate-1/2" Thick	33.1 to 35.8 HRC (Ultrasonic) 347 to 386 BHN (Telebrineller)
147	Eastbound/ Downstream	L10/Top Splice Plate-7/16" Thick	33.9 to 36.8 HRC (Ultrasonic) 358 to 371 BHN (Telebrineller)
273	Eastbound/ Downstream	U 16/KY External Inboard Splice Plate-1/2" Thick	30.9 to 36.2 HRC (Ultrasonic) 350 BHN (Telebrineller)
274	Eastbound/ Downstream	U 16/KY External Outboard Splice Plate-1/2" Thick	28.0 to 32.9 HRC (Ultrasonic) 337to 340 BHN (Telebrineller)
275	Eastbound/ Downstream	U 16/OH External Inboard Splice Plate-1/2" Thick	35.3 to 35.6 HRC (Ultrasonic) 355 to 415 BHN (Telebrineller)
276	Eastbound/ Downstream	U 16/OH External Outboard Splice Plate-1/2" Thick	29.9 to 38.8 HRC (Ultrasonic)

Table 5. Timeline for Out-of-Spec./Defective ASTM A 514 Steel on the I-275 Combs-Hehl Bridges		
Item	Date(s)	Event
	10/23/06 to 11/3/06	URS Corp. conducting fracture-critical inspection of the I-275 Bridges found 3 cracked splice plates on westbound bridge
	7/10/07	KTC submitted an initial proposal to KYTC to investigate splice cracking
	5/31/08 to 6/1/08	Intech Contracting replaced the 3 cracked splice plates on the westbound bridge
	7/29/08	IMR reported preliminary findings on mechanical properties of cracked splice plates to KTC
	8/26/08	IMR-KTC reported finding defective steel to KYTC officials
	8/28/08	IMR-KTC-HTT began investigating hardness test methods
	9/15/08	KTC submitted a proposal to scope field NDE testing of all A 514 steel on the I-275 bridges
	9/30/08	Intech Contracting established traffic control on the westbound bridge downstream and the eastbound bridge upstream
	10/1/08	HTT provided one technician to begin hardness testing on westbound bridge
	10/1/08	Burgess & Niple technicians conducting fracture-critical inspection on the bridge found a cracked splice plate at tower U16 on downstream truss of the eastbound bridge
	10/2/08	Intech Contracting shifted the eastbound bridge upstream truss traffic control to the downstream truss
	10/3/08	KTC and HTT personnel inspected the cracked splice plate and found that it to be defective A 514 steel
	10/3/08	KYTC posts the eastbound bridge at 6,000 lb and begins 24/7 police surveillance to prevent trucks from using the bridge
	10/6/08	Mistras Inc. provides three NDE technicians on the project
	10/14/08	An NDE technician finds a second cracked splice plate at tower (U16) on downstream truss of the eastbound bridge
	10/16/08	Teleconference with KYTC, ODOT and KTC on proposed ultrasonic shear wave testing of splice plates to detect cracks
	10/19/08	Intech Contracting shifted the eastbound bridge downstream truss traffic control to the upstream truss
	10/20/08	HTT personnel conducted ultrasonic shear wave testing at tower (U16) on downstream truss of westbound. No cracks were found
	10/20/08	Intech Contracting changes the traffic control on the westbound bridge from the downstream to upstream truss

	10/21/08	HTT personnel conducted ultrasonic shear wave testing at tower (U16) on upstream truss of westbound bridge and upstream truss of eastbound bridge. No cracks are found
	11/3/08	Mistras provides two new NDE technicians as replacements
	11/20/08	Testing is completed on eastbound upstream truss. Intech Contracting shifts traffic control to downstream truss
	11/23/08	Testing is completed on westbound upstream truss. Intech Contracting shifts traffic control to downstream truss
	12/5/08	Field testing is completed on both downstream trusses and on project. Mistras technicians demobilize and turn in equipment and log books.
	12/11/08 to 12/13/08	Intech Contracting removes defective A 514 splice plates from U16 locations on the eastbound bridge
	2/1/08 to 6/1/08	Kay and Kay Rigging removes/remedies the balance of the defective A 514 splice plates/gussets on the two bridges
	6/21/08	IMR publishes report no. 27958 addressing testing of defective A 514 steel detected on project

8. FIGURES

Figure 1. I-275 Combs-Hehl Twin Bridges over the Ohio River (Courtesy J. Mecklenborg).

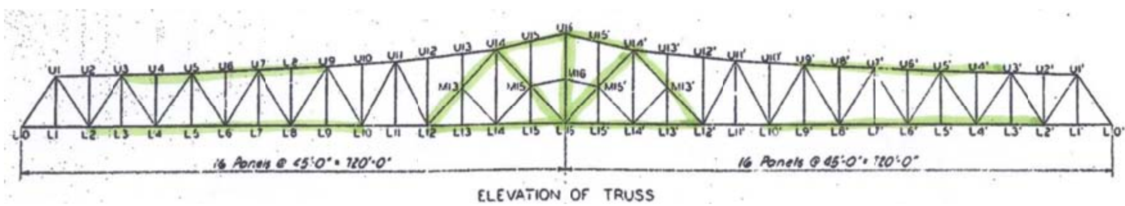

Figure 2. I-275 Combs-Hehl Bridge Truss Showing Highlighted Locations of ASTM A 514 Steel.

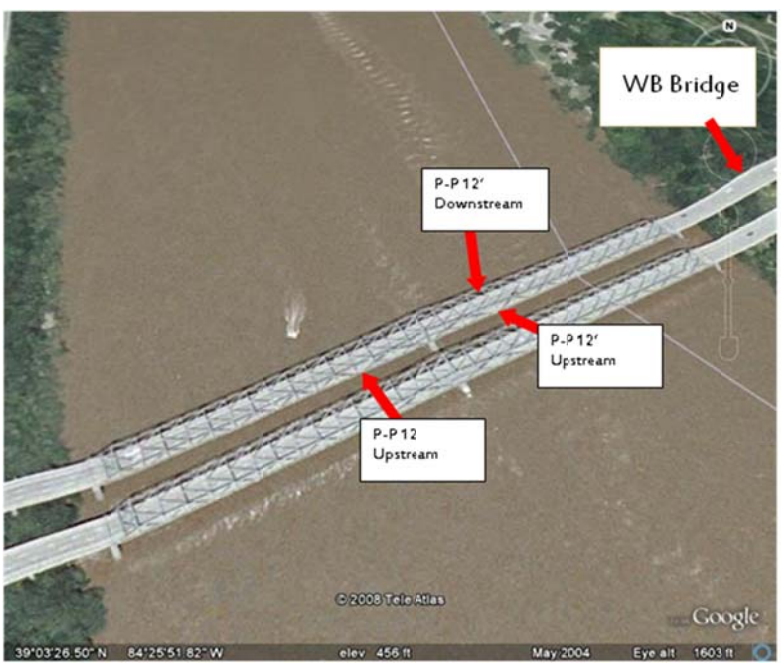

Figure 3. I-275 Combs-Hehl Twin Bridges Showing Locations of Cracked Splice Plates on Westbound Bridge.

Figure 4. Crack in 3/8-Inch Thick Splice Plate at Panel Point L12’ on the Downstream Truss of the Westbound Bridge (Courtesy of URS Corp).

Figure 5. Installation of Replacement 3/8-Inch Thick Splice Plates on May 31, 2008.

Figure 6. Microstructure of Improperly Tempered A 514 Steel from Cracked Splice Plates (1000X Magnification). Etchant: 2% Nital.

Figure 7. Photomicrograph montage of Intergranular Cracking Emanating from Corrosion Pit in A Cracked Splice Plate (250X Magnification). As - Polished.

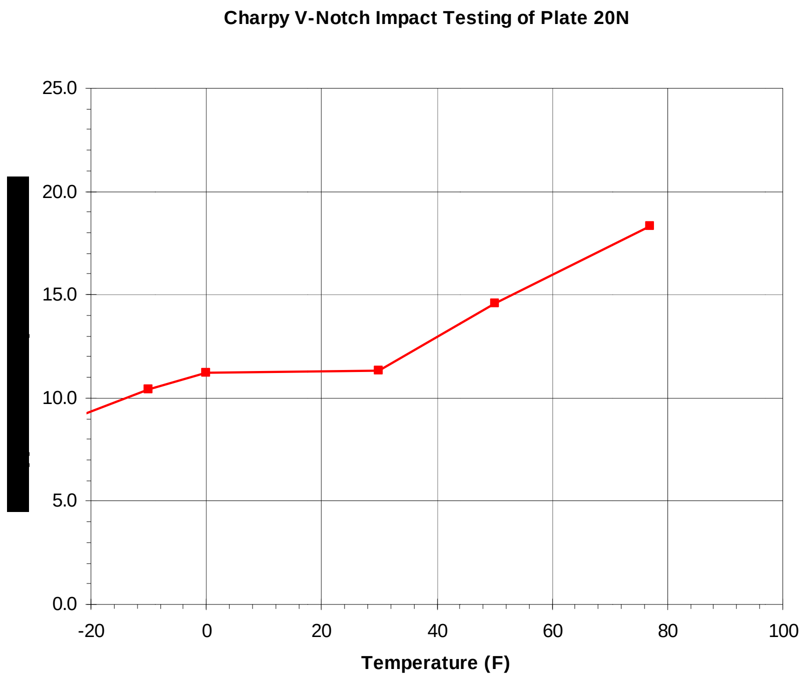

Figure 8. Charpy Impact Values (ft-lb) v. Temperature for Out-of-Spec./Defective A 514 Steel from the I-275 Combs-Hehl Westbound Bridge.

A.


B.

Figure 9 A. Quenching A 514 Pieces after Re-Heating (and Prior to Re-Tempering) and B. Charpy Impact Testing Re-Tempered Pieces to Investigate the Relationship between Indentation Hardness and Impact Toughness.

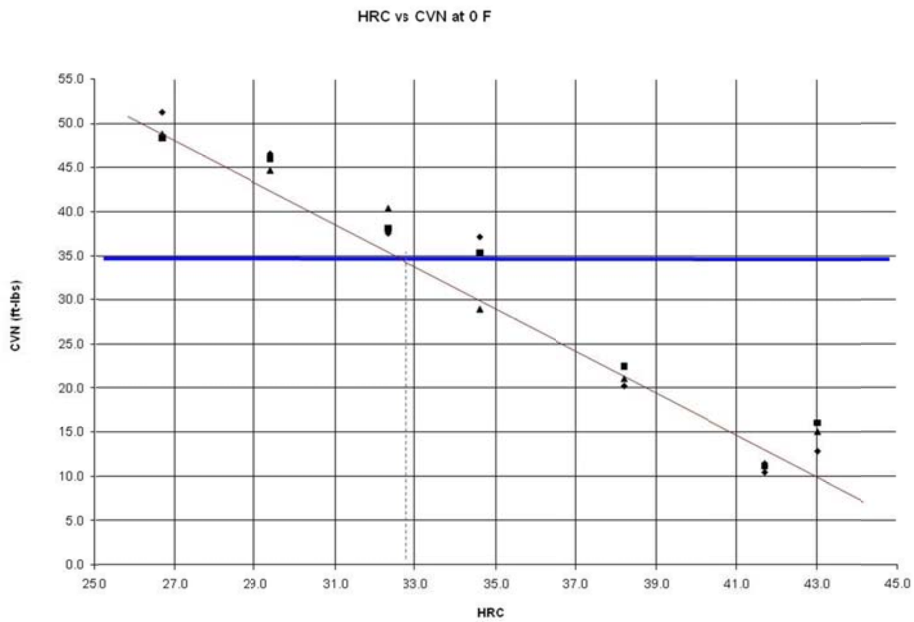

Figure 10. Charpy V-Notch Impact Test Values vs. Rockwell C Hardness for A 514 Steel with Different Tempering Treatments


Figure 11. Performing Ultrasonic Hardness Testing on Defective A 514 Steel in Vertical Test Orientation by Pressing Probe into the Steel.

Figure 12. Screen Read-Out of GE/Krautkramer MIC 20 for Tests on Defective Steel. Individual Test Values are indicated by Red Numbers (e.g. 41.5 HRC) in Upper Right Corner of Screen. The Running Average of a Series of Tests is indicated by White Numbers above (e.g. 40.5 HRC).

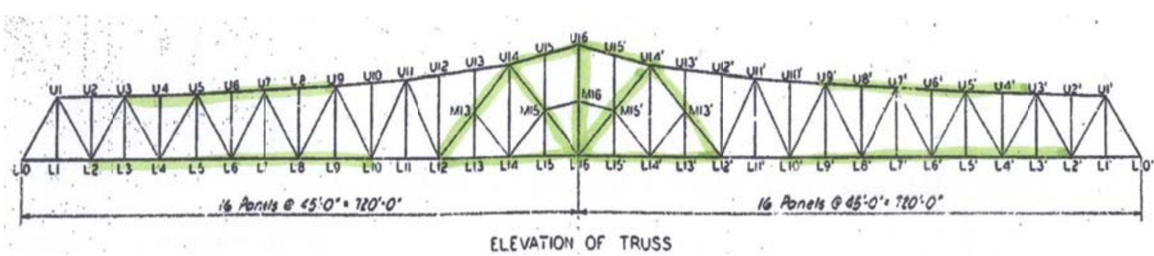

Figure 13. I-275 Combs-Hehl Bridge Truss Showing Highlighted (Green) Locations of A 514 Steel.

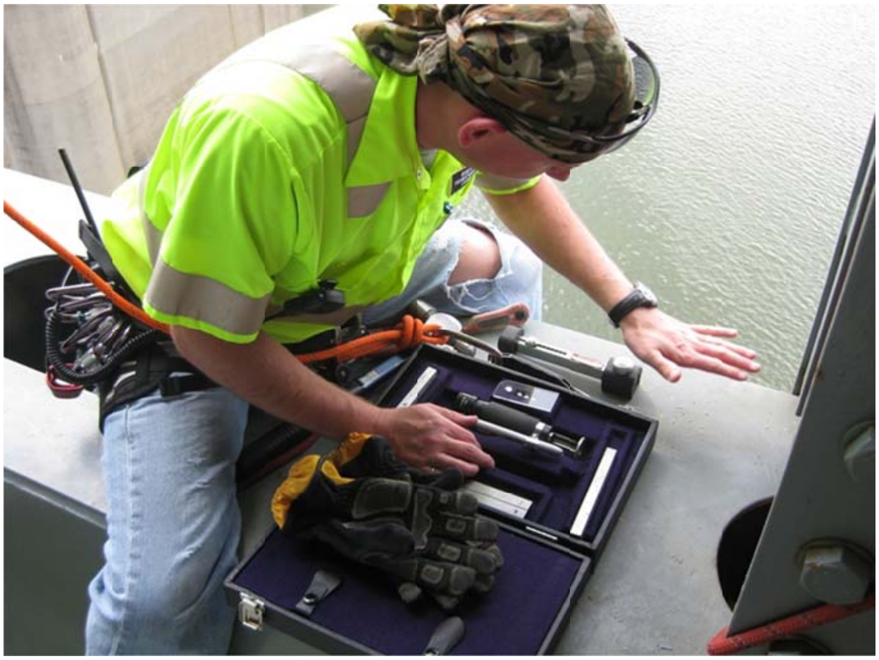

Figure 14. Telebrineller Unit (to Left of Carrying Case) Prior to Use.

Figure 15. NDE Technician Measuring Telebrineller Mark Diameter on an Upper Chord Member of the I-275 Westbound Bridge.

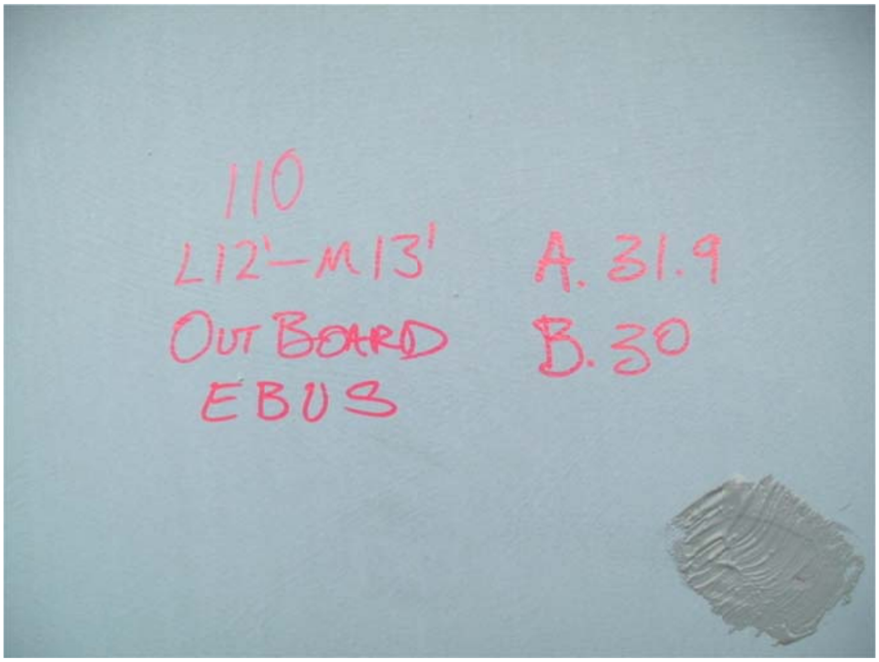

Figure 16. Photograph of Field Hardness Test Location/Result on I-275 Bridge. Note That a Test Location has been repainted.

Figure 17. Lane Closure Set-up on the Eastbound Bridge (10/13/08).

Figure 18. Intech Worker In-training to Remove Leaded Paint for Test Patches.

Figure 19. A Cracked 1/2” Inboard Splice Plate at the Tower of the Eastbound Bridge Downstream on the Ohio Side of the Bridge.

Figure 20. The HTT NDE Supervisor Teaching Mistras NDE Technicians to Perform Ultrasonic Hardness Tests at IMR.

Figure 21. Special Calibration Plate Used for Nondestructive Evaluation of 1/2” Splice Plates at Tower (U16) Locations on the Two I-275 Bridges.

Figure 22. HTT NDE Supervisor Performing Ultrasonic Shear Wave Inspections on a 1/2" Splice Plate on the Downstream Truss of the Westbound Bridge.

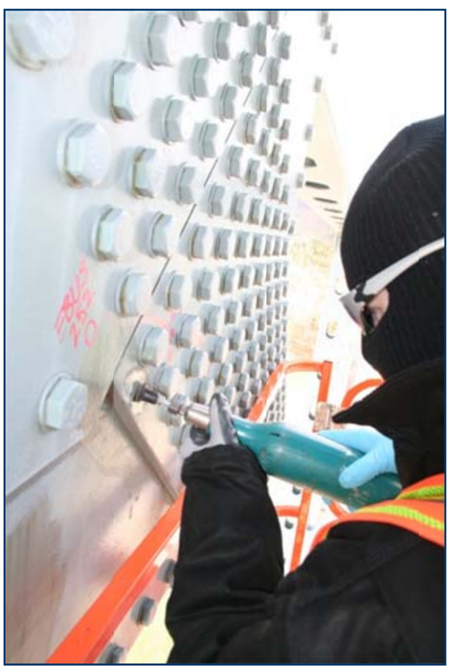

Figure 23. IMR Technician Polishing A 514 Steel Splice Plate that Provided Low Hardness Readings Prior to Making a Replica of the Surface Microstructure.

Figure 24. Replica of A 514 Steel Showing Ferritic-Fine Carbide Microstructure (~600X).

Figure 25. IMR Technician Cutting Corner Specimen from A 514 Steel Splice Plate that Provided Low Hardness Readings.

Figure 26. Surface Decarburized Layer-Cross Section from Extracted A 514 Steel Coupon Removed in Figure 24 (~100X).

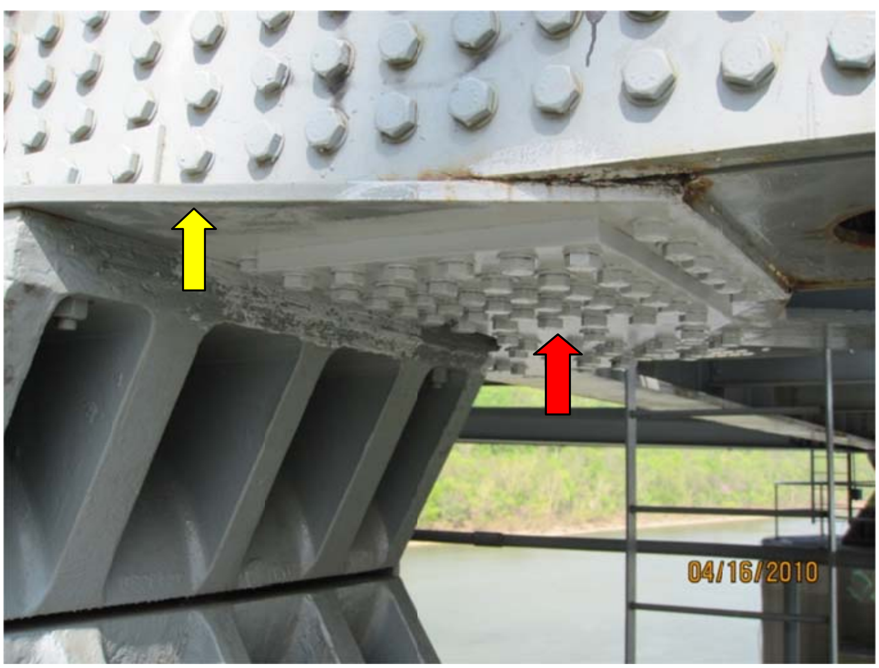

Figure 27. Reinforcing Plate (Red Arrow) Lapped over Defective ASTM A 514 Horizontal Gusset Plate (Yellow Arrow).

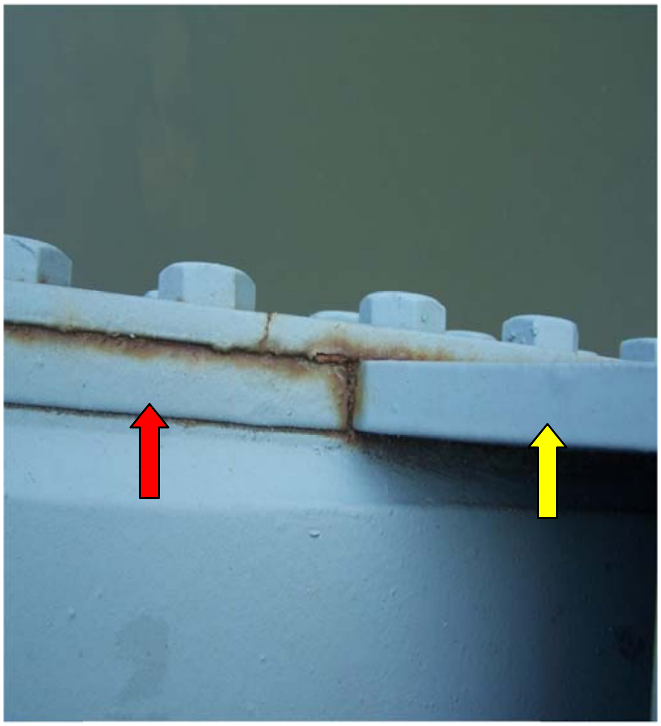

Figure 28. Filler Plate (Red Arrow) Adjacent to Gusset Plate (Yellow Arrow) on Lower Chord of Westbound Bridge. Note the Cracked 3/8” Thick Splice Plate.

8. APPENDIX A

University of Kentucky
Kentucky Transportation Center
Theodore Hopwood II, P.E.
176 Raymond Building
Lexington, KY 40506

REPORT NO. 26789

August 12, 2008

METALLURGICAL FAILURE ANALYSIS OF CRACKED SPLICE PLATES FROM THE I-275 COMBS-HEHL BRIDGE: DATA

METALLURGICAL SERVICES
LOUISVILLE LLC
4102 Bishop Lane, Louisville, KY 40218

ACCREDITED
ISO 17025
Mechanical 1140-03
Chemical 1140-04

Report By:

John P. Jendrzejewski, Ph.D.

E-mail: john@imrlouisville.com

Confidential and Privileged Information

University of Kentucky
Kentucky Transportation Center
176 Raymond Building
Lexington, KY 40506

Attention: Theodore Hopwood II, P.E.

IMR-MSL Report No. 26789

METALLURGICAL FAILURE ANALYSIS OF CRACKED SPLICE PLATES FROM THE I-275 COMBS-HEHL BRIDGE: DATA

Confidential and Privileged Information

SUMMARY:

Metallurgical testing on three splice plates from the I-275 Combs-Hehl Bridge is summarized in the following pages. In addition to the data provided herein, photographs, photomacrographs and photomicrographs of the cracks were provided in an electronic format, i.e. CD.

ANALYTICAL PROCEDURES

I. Visual Examination

- A. Visual Observations
- B. Photography (digital)
- C. Dimensional Measurements
- D. Optical Stereomicroscopy, magnifications up to 75X

II. Chemical Analysis: Base Metal

- A. Optical Emission Spectroscopy, ASTM E415-99a / E1086-94(00)
- B. Carbon and Sulfur by Combustion Analysis, ASTM E1019-03

III. Scanning Electron Microscopic Examination

- A. Scanning Electron Microscopy (SEM), permits examination at high magnification and with great depth of field

IV. Microanalysis: Deposits, Corrosion Products, etc.

- A. Energy Dispersive X-ray Spectroscopy (EDS) in conjunction with SEM, permits detection of all elements greater than beryllium in atomic weight, ASTM E1508-98(03).

V. Mechanical Testing

- A. Rockwell Hardness, ASTM E18-07
- B. Microindentation Hardness Testing, ASTM E384-08
- D. Tensile Testing, ASTM E8-04
- E. Charpy Impact Testing, ASTM E23-04
- F. Hardness Conversion, ASTM E140-07

VI. Metallography

- A. Microstructural Analysis using Light Metallurgical Microscope(s), ASTM E3-01

Respectfully submitted; Concurrence:

John P. Jendrzejewski, Ph.D. Chief Metallurgist / Failure Analyst	8/12/08 Date	Brett A. Miller, P.E. Senior Metallurgical Engineer / Failure Analyst	8/12/08 Date

ISO 17025
Mechanical 1140-03
Chemical 1140-04

TABLE 1

Chemical Analysis

Values in Weight Percent

ELEMENT	PANEL "20N" (I275W North Face 20)	PANEL "20S" (I275W 20S)	PANEL "12S" (I275 12S)	ASTM A514 Grade B SPECIFICTIONS
Carbon	0.21	0.21	0.21	0.12 – 0.21
Silicon	0.28	0.29	0.29	0.20 – 0.35
Manganese	0.88	0.90	0.88	0.70 – 1.00
Phosphorus	0.008	0.008	0.007	0.035 max
Sulfur	0.022	0.021	0.022	0.035 max
Chromium	0.52	0.53	0.52	0.40 - 0.65
Molybdenum	0.17	0.17	0.17	0.15 – 0.25
Nickel	0.05	0.05	0.05	------
Aluminum	0.035	0.034	0.035	------
Cobalt	< 0.01	< 0.01	< 0.01	------
Copper	0.02	0.02	0.02	------
Niobium	< 0.01	< 0.01	< 0.01	------
Titanium	0.02	0.02	0.02	0.01 – 0.03
Vanadium	0.05	0.05	0.05	0.03 – 0.08
Tungsten	< 0.01	< 0.01	< 0.01	------
Lead	< 0.01	< 0.01	< 0.01	------
Boron	0.0016	0.0017	0.0014	0.0005 – 0.005
Iron	Remainder	Remainder	Remainder	Remainder

SPECIFICATION(S)/METHOD(S)/PROCEDURE(S) FOLLOWED:

Optical Emission Spectroscopy (ASTM E415-99a (05))
Carbon and Sulfur by Combustion Analysis (ASTM E1019-03)

EQUIPMENT USED:

Spectromax CCD
Eltra CS-800 Carbon/Sulfur Determinator

TENSILE TEST & ROCKWELL HARDNESS RESULTS ON CRACKED PLATES

SAMPLE	Tensile Strength (ksi)	Yield Strength (ksi)	% Elongation in 2”	Rockwell Hardness (HRC)*
Plate “20N” (Long.)	192.7	177.1	13	42
Plate “20N” (Trans.)	196.7	179.4	8	-
Plate “20S” (Long.)	199.6	178.2	13	40
Plate “20S” (Trans.)	195.4	180.8	8	-
Plate “12S” (Long.)	195.0	178.6	13	41
Plate “12S” (Trans.)	193.6	175.0	7	-
ASTM A 514 Specifications	110 - 130	100 min.	18 min.	~22-31

* Average of Four Readings

ROCKWELL HARDNESS RESULTS PLATE 20N HEAT TREATED COUPONS

SAMPLE	Rockwell Hardness (HRC)*
Plate “20N “ Normalized**	24
Plate “20N” Water Quenched***	47
Plate “20N” Water Quenched/Tempered @ 400^{o}F	46
Plate “20N” Water Quenched/Tempered @ 800^{o}F	38
Plate “20N” Water Quenched/Tempered @ 1,000^{o}F	32

* Average of Four Readings

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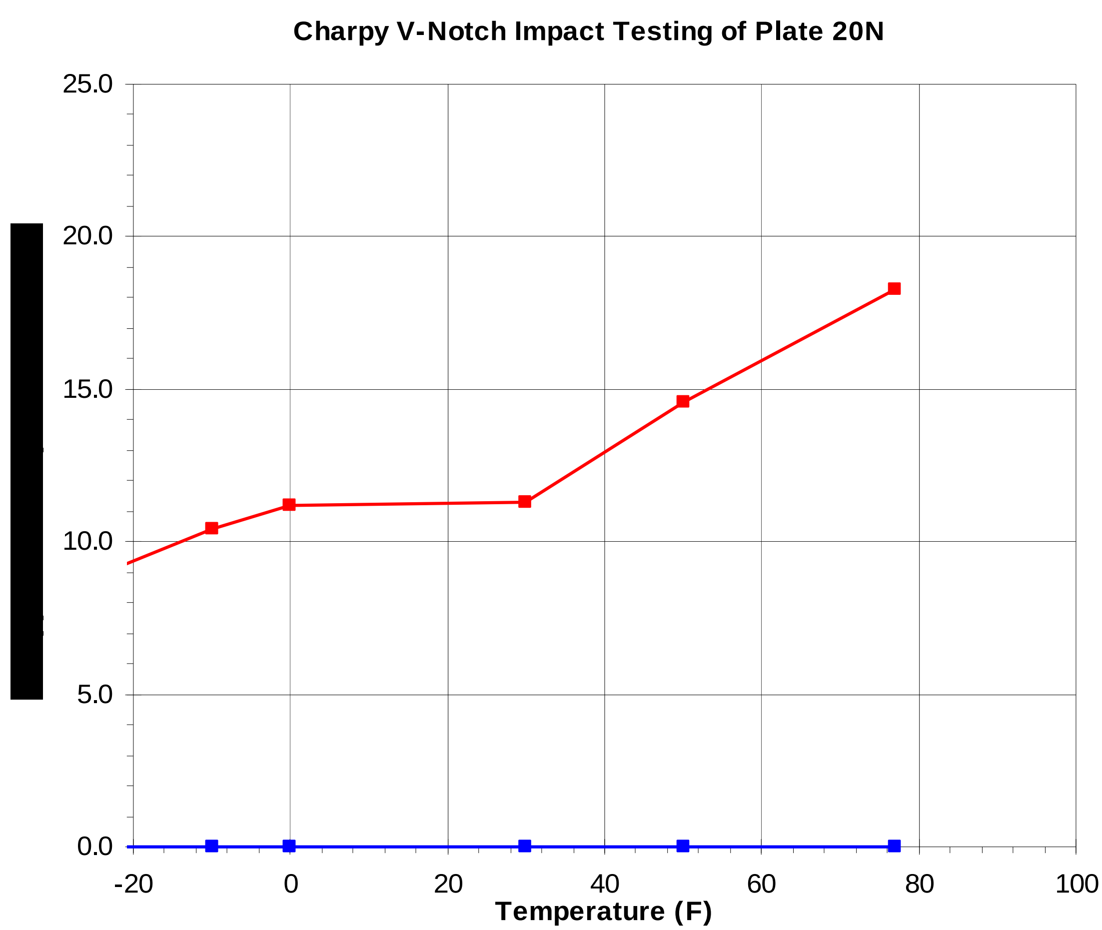
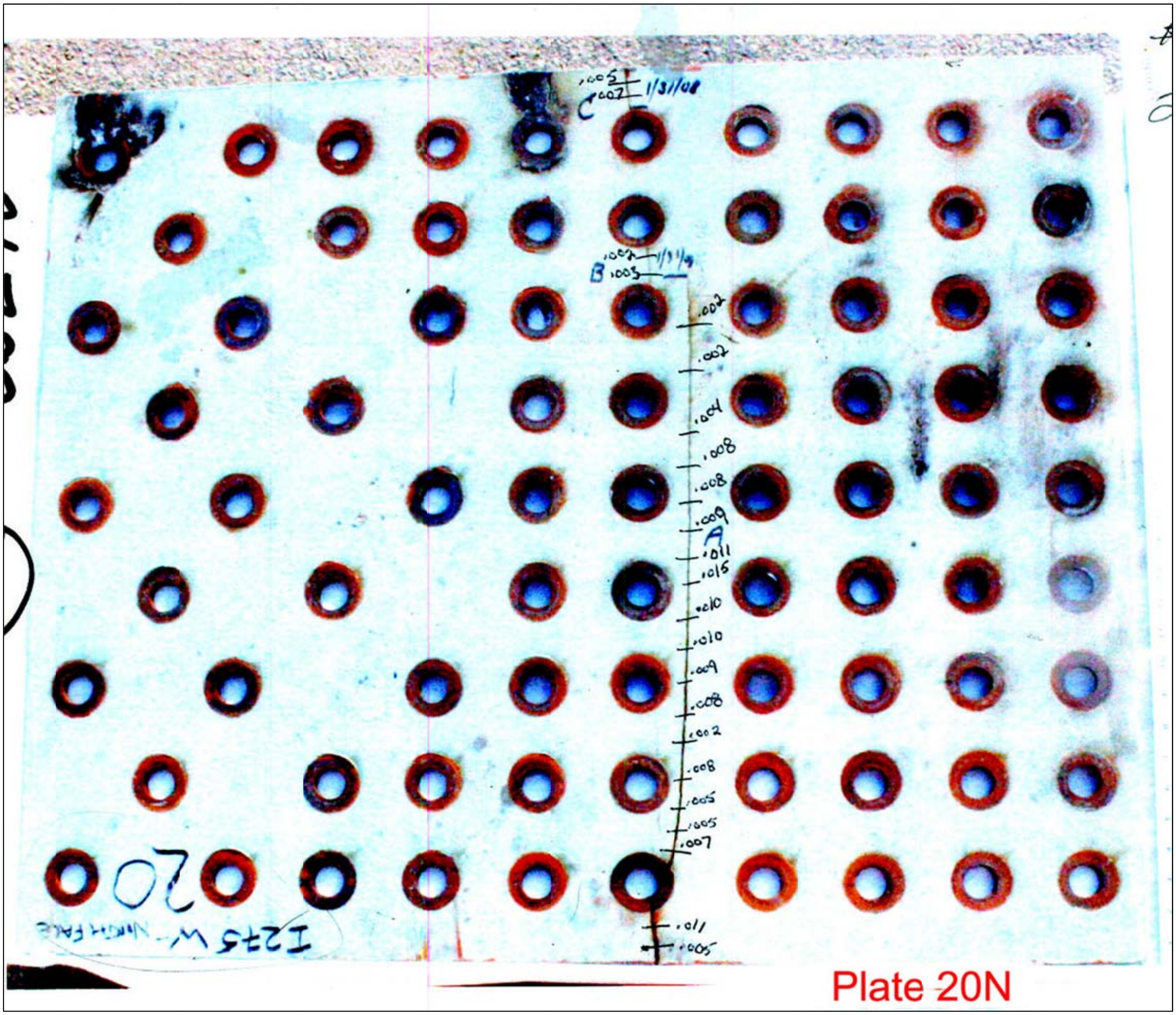
**** Normalized Heated to 1,600^{o}F and Air Cooled
*****Water Quenched After Heating to 1,600^{o}F

CHARPY V-NOTCH RESULTS

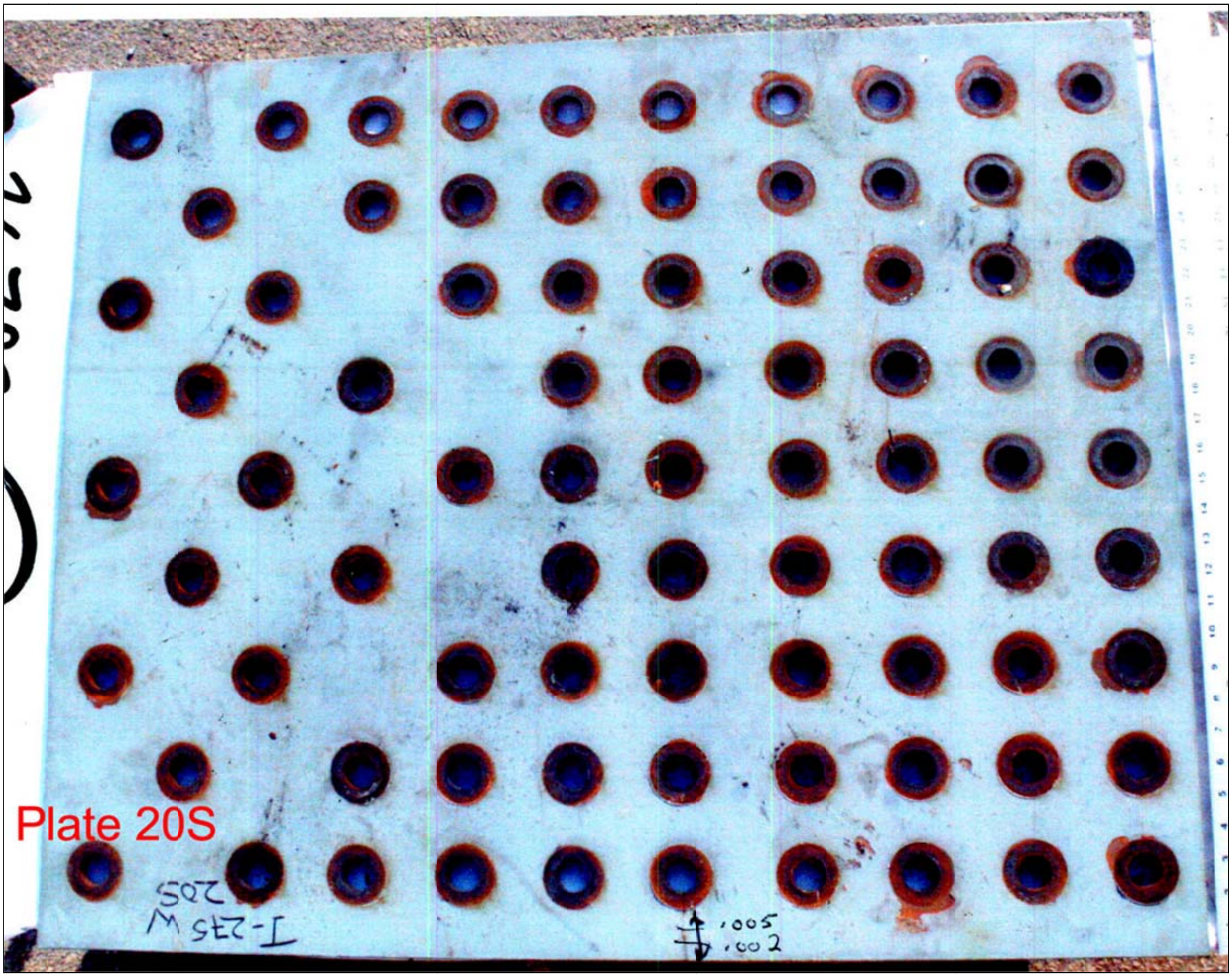
REPORT NO.:	26789	**VENDOR:**	University of Kentucky
PROJECT NAME:	Ductile Brittle Transition Temp.	**HEAT NO.:**	None provided
SUBJECT:		**CONTACT:**	Ted Hopwood
TEST SPEC.:	ASTM E23-94a	**DATA BY:**	SB
DESCRIPTION:	Type A Charpy Impact Specimen	**DATE:**	7/7/2008

Test Temperature (F)	**Charpy Impact (ft-lb)**					Comments
	Plate 20N	**Individual Tests**				
-30	8.3	(8.2,7.7,9.1)				
-10	10.4	(11.0,10.4,9.6)				
0	11.2	(10.4,11.2,11.5)				
30	11.3	(11.7,11.5,10.6)				
50	14.6	(14.6,14.7,14.4)				
77	18.3	(18.7,17.8,19.2)				

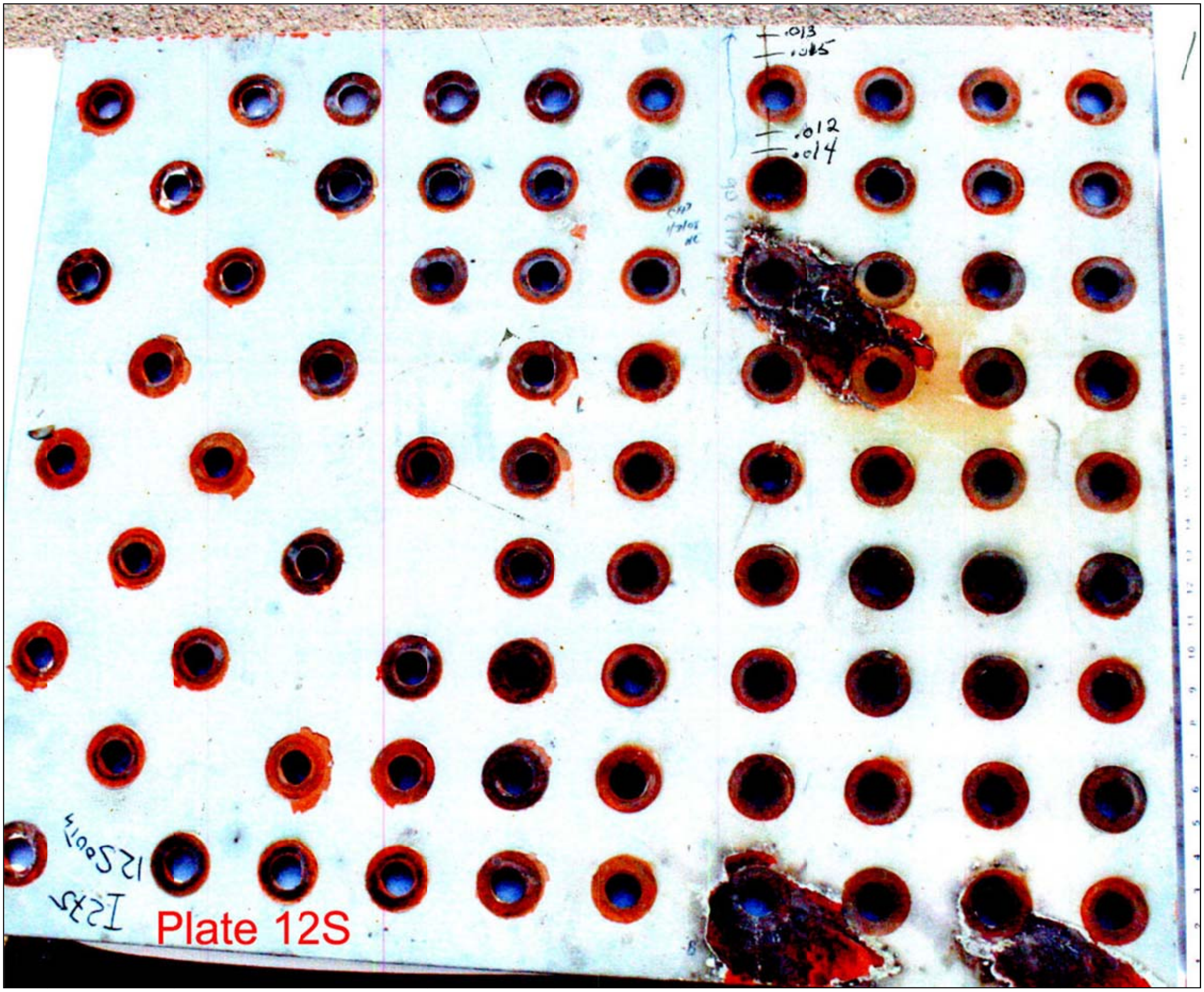




Displacement across the crack from Plate 20N (Values in inches) Range 0.002" – 0.015"



Displacement across the crack from Plate 20S (Values in inches) Range 0.002" – 0.005"



Displacement across the crack from Plate 12S (Values in inches) Range 0.012" – 0.015"

9. APPENDIX B

Hardness Testing of Additional Samples from the Combs-Hehl Bridge

University of Kentucky
KY TPN Center
176 Raymond Build
Lexington, KY 40506

Attention: Ted Hopwood

Confidential and Privileged Information

REPORT No. 30383

June 9, 2010

Report By:

John P. Jendrzejewski, Ph.D.

METALLURGICAL SERVICES
LOUISVILLE LLC

4102 Bishop Lane, Louisville, KY 40218

ACCREDITED

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University of Kentucky
KY TPN Center
176 Raymond Build
Lexington, KY 40506

June 9, 2010

Attention: Ted Hopwood

Report No. 30383

Hardness Testing of Additional Samples from the Combs-Hehl Bridge

SUMMARY

The results of the laboratory hardness testing of ten (10) additional plate samples or coupons removed from the Combs-Hehl bridge in northern Kentucky are presented in this report in Table 1 (i.e. samples #8-#17). All samples exceeded the maximum hardness requirements of ASTM A 514. Also given in Table 1 are the average hardness measurements from the initial seven plates that were removed from the bridge, i.e. samples #1-#7, (reference IMR Louisville Report #27958 dated March 6, 2009).

ANALYTICAL PROCEDURE

I. Mechanical Testing

A. Rockwell Hardness, ASTM E18-07

RESULTS

The results of the Rockwell hardness testing conducted in the laboratory are presented in Table 1.

Respectfully submitted:

John P. Jendrzejewski, Ph.D.
Chief Metallurgist / Failure Analyst

Concurrence:

Brett A. Miller, P.E.
Senior Metallurgical Engineer / Failure Analyst

ACC REP ITED
TEC
1'43 ca+1142. C4

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TABLE 1

HARDNESS SUMMARY OF LABORATORY TESTED SAMPLES REMOVED FROM THE COMBS-HEHL BRIDGE

Splice Plate Description	Sample Identification*	Rockwell Hardness (HRC)**
#1. Cracked, Lower Chord "20N"	WB-DS OH OB- L12'	42
#2. Cracked, Lower Chord "20S"	WB-US OH OB- L12'	40
#3. Cracked, Lower Chord "12S"	WB-US KY OB- L12	41
#4. Cracked, Upper Chord (#274)	EB-DS KY OB- U16	40
#5. Cracked, Upper Chord (#275)	EB-DS OH IB- U16	41
#6. Un-Cracked, Upper Chord (#273)	EB-DS KY IB- U16	41
#7. Un-Cracked, Upper Chord (#276)	EB-DS OH OB- U16	42
#8. Un-Cracked, Lower Chord (#147)	EB DS- L10	42
#9. Un-Cracked, Upper Chord (#274)	EB US- U16	42
#10. Un-Cracked, Lower Chord (#151)	WB US- L12	41
#11. Un-Cracked, Upper Chord (#273)	WB US- U16	42
#12. Un-Cracked, Upper Chord (#274)	WB US- U16	42
#13. Un-Cracked, Lower Chord (#152)	WB DS OB- L12	42
#14 Un-Cracked, Lower Chord (#151)	WB DS IB- L12	43
#15. Un-Cracked, Upper Chord (#177)	EB US- L16	38
#16. Un-Cracked, Lower Chord (#177)	WB US- L16 Hor. Gusset	38
#17. Un-Cracked, Lower Chord	WB US IB- L2'	36
ASTM A 514 Specifications	---	—22-31

***KEY:**

EB = Eastbound Bridge
WB = Westbound Bridge
US = Upstream
DS = Downstream
KY=Kentucky Side
OH = Ohio Side
IB = Inboard (Facing Road)
OB = Outboard (Facing River)

**Average Hardness of at Least 4 Measurements

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For more information or a complete publication list, contact us at:

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