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Forensic Engineering Investigation of a High-Voltage Transmission Line Anchor Shackle Failure

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Abstract

A forged alloy steel anchor shackle, one of a batch of more than 2,600 produced for the project, failed catastrophically in service on a newly erected 66-kilometer high-voltage transmission line in northern Canada. A failure analysis led to a hypothesis that forging laps had created the critical crack size to initiate propagation under cold weather conditions. An extensive Charpy fracture toughness test program based on CAN/CSA C83.115-96 parameters was performed on 150 shackles, but the data did not support the initial hypothesis of temperature dependence. The forensic engineering team designed experimental tensile tests at ambient temperatures as low as -40°C to evaluate the propagation response of lap cracks in a statistically valid sampling of shackles. The trimmed forging flash area disguised laps from the manufacturing process, and subsequent galvanizing steps prevented detection by magnetic particle inspection. A focused recommendation for removal and replacement of the shackles was issued for those bearing major loads in the tower array.

Keywords

High-voltage transmission line, shackle hardware, Charpy tensile test, low-temperature fracture toughness, experimental design, statistical sample, forensic engineering

Failure Context and Procurement History

The forensic engineers were engaged on behalf of the owner to confirm the probable cause of the fracture of the single anchor shackle's arms in service on a new transmission line. Standards and specifications that are part of the procurement documents were studied to determine how a decision on fitness for service could be derived. The goal was to provide a technically based criteria for deciding whether all, most, or some fraction of the shackle batch should be replaced while neither endangering the public nor compromising the integrity of the transmission line.

Figure 1
Typical Number 9 anchor shackle with clevis pin.

The Number 9 anchor shackles (**Figure 1**) are employed in an array to support insulators on the steel towers (**Figure 2**). The load path goes through the two arms

Figure 2
High-voltage transmission tower.

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of the shackle, splitting evenly at the eyes by the contact from the clevis pin. By inspection, the cross-sectional area at the midpoint is therefore at the maximum tensile stress when the insulator assembly is loaded in service. Number 9 shackles have a nominal rating of 440 kiloNewtons (kN). The load divided by the cross-sectional area defines the tensile stress in the arms. The position of the broken shackle on the tower is depicted in **Figure 3**.

Statistical Quality Control in Manufacturing Processes and Procurement Documents

Contemporary manufacturing processes employ control systems that are set up to ensure that the quality of raw materials will conform with the engineering design requirements. Master procurement document(s) address these criteria and lay out the means and methods by which the assurance can be obtained to a satisfactory level based on statistical theory. Acceptable Quality Level (AQL) was used because it is uneconomical to test every item in a lot, and these scientifically based sampling criteria are intended to provide the end-user with confidence of the quality of the components[1].

The CAN/CSA C83-96 (2011) "Communication and Power Line Hardware" standard[2] employs the AQL concept to guide the management of risks associated with a product possessing an attribute that is defective. AQL underlies the decision-making process regarding acceptance or rejection of a lot of raw material and (later in the process) the finished products. These are not done in the same way because of process constraints and economic limitations. Inspection by Variables is cited as an "inspection that actual measurement on a continuous scale is made on the unit or article for the quality characteristic under consideration (e.g., tensile testing of steel)."

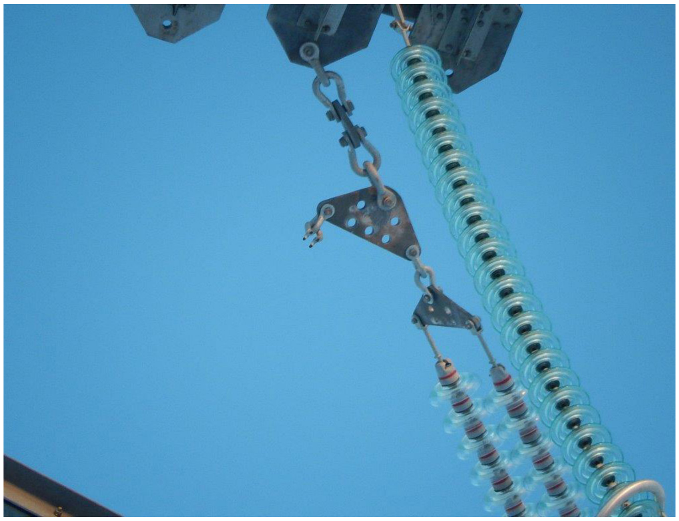

Figure 3
Fractured shackle on the tower.

This contrasts with Inspection by Attributes, which, as set out on page 18, Section A1.4 of the standard, "determines whether the unit or article does or does not conform to the specified requirements for the quality characteristics under consideration (e.g., "GO" or "NO-GO" gauging)".

Defects are discussed in Table 3 of CAN/CSA C83-96, which defines the general classes of defects as follows:

<u>Critical</u> — *Where a failure to meet the specified requirement, through functional failure, would surely result in danger to life. (Class A AQL percent defective* ***0.015%)***

<u>Very Serious</u> — *Where a failure to meet the specified requirement, through functional failure, would surely result in hazardous conditions to personnel or high restoration costs or high consequential costs or any combination of these. (Class B AQL percent defective* ***1.0%)***

According to the Anchor Shackle appendix of CAN/CSA C83.115-96, Class A defects (defined as a critical functional failure) are NOT allowed. It designates surface defects (iii) and energy absorption/toughness (iv) as very serious, or Class B, defects in shackles. The shackle failure that occurred in service may have automatically disqualified the whole batch.

Sampling Plans

The CAN/CSA C83-96 Appendix A sampling programs are recommended to be used for qualification of the component's attributes, while Appendix B inspection by variables programs would be employed for costly destructive testing, such as tensile tests. For example, for a Single Sampling Plan for a run of 1,301 to 3,200 pieces, the sample size would be 150 pieces, whereas under Appendix B, for under 5,000 pieces in the lot, the sample size would be 5. The narrative explicitly states that the best approach for detecting Class A defects is statistical quality control during the raw material selection and production processes.

Participants in the Investigation Process

The utility commissioned Company C, an engineering firm, to complete the design, procurement, and construction of the transmission line. Company A was a European manufacturer of anchor shackles. Company B was a testing laboratory in Europe. Company D and E were both independent testing laboratories in Canada commissioned by the forensic engineer. Company E was a highly

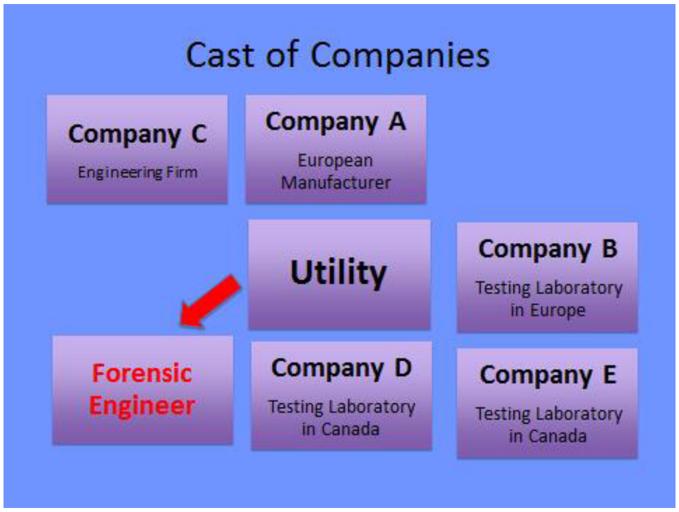

Figure 4
Participants in the investigation.

qualified aerospace metallurgical laboratory (**Figure 4**).

The Anchor Shackle Manufacturing Process at Company A

Six-meter-long bars of 32-mm-diameter 41Cr4 type (equivalent to AISI 5140) heat-treatable and hardenable low alloy steel were cut to size and then hot-forged to shape the anchor shackles. Forging uses mechanical compressive force to plastically deform and change the metallurgical structure of an object, giving it improved strength characteristics. The forging tools may leave flashing when the hammer and anvil are not perfectly aligned; this flashing is typically trimmed as an intermediate step. A "lap" may form if the flashing metal is folded over at the edge of the main body of the forging. Heat treatment (including quenching and tempering) produced the tempered martensitic microstructure, but this process was not revealed in the reviewed documents. A galvanizing step follows in which the product is dipped into a molten zinc aluminum liquid-phase solution. Assembly of the clevis pin and self-locking cotter pins are completed to create the ready-to-use shackle in the final manufacturing step. Approximately 2,600 shackles were made in batch code 2525 by Company A.

According to production records, a sample of the steel bar raw material for the batch was qualified and accepted for cold weather behavior by Charpy test specimens that exceeded the required minimum absorption energy with 24 to 34 Joules at -20°C. The anchor shackles were sampled and subjected to a quality control department tensile test. Each specimen met the rating criteria of CAN/CSA 83.115-96[3] during the room temperature tests, allowing the batch to be accepted and released to the project.

Observations

Company B Failure Analysis Report

The single Number 9 anchor shackle that fractured on the transmission line is shown in **Figures 5** and **6**. Four fracture surfaces of the field failure shackle were examined with metallographic techniques on behalf of the utility and Company A by the laboratory of Company B in Europe. These fractures are displayed in **Figures 7, 8, 9,** and **10**. Each fracture was individually characterized by high-power microscopy. Fracture origins were found along the inboard edge of the eye at forging laps on two of the four fracture surfaces, while the other fractures appeared to be consequential to the two primary fractures. Thirty-one shackles from Batch 2525 were examined and tested.

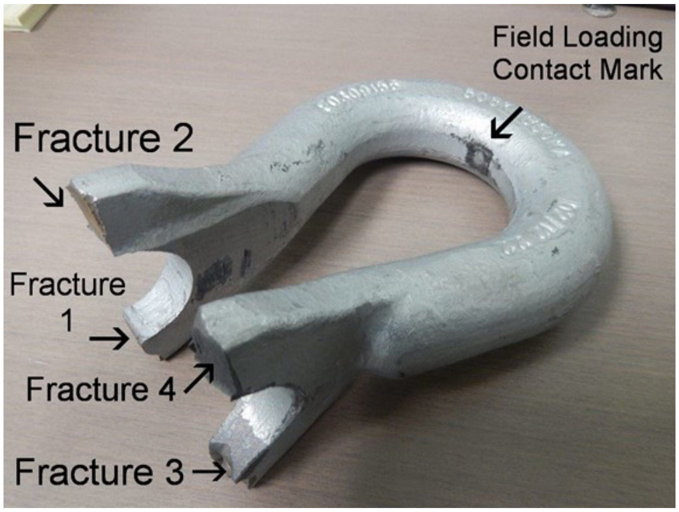

Figure 5
Fractured anchor shackle.

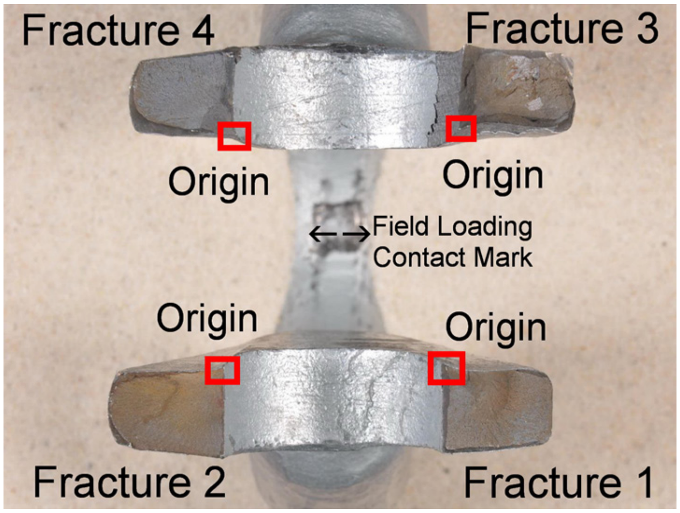

Figure 6
End view of fractures on anchor shackle.

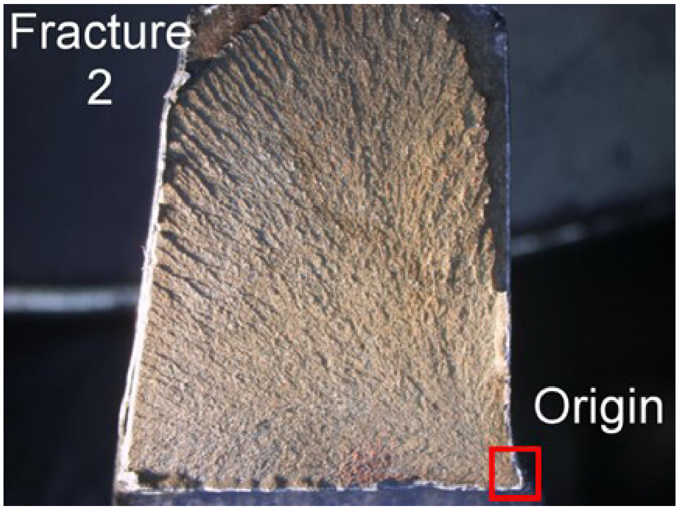

Figure 7
Shackle fracture 2 at the inner eye, origin at lower right.

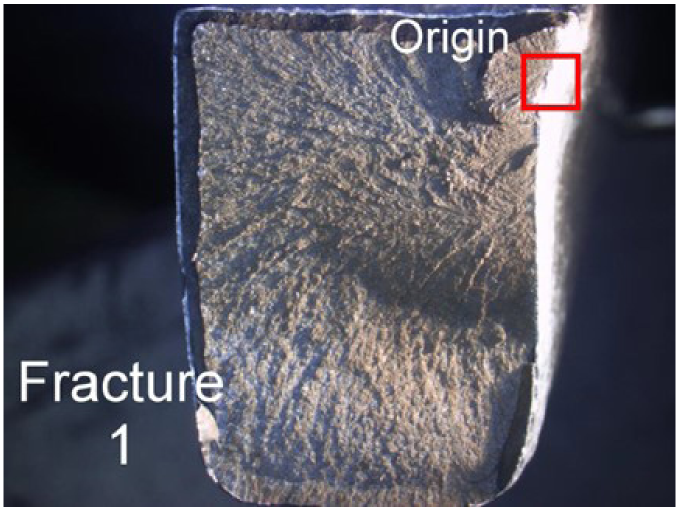

Figure 8
Shackle fracture 1 at the inner eye, origin at upper right.

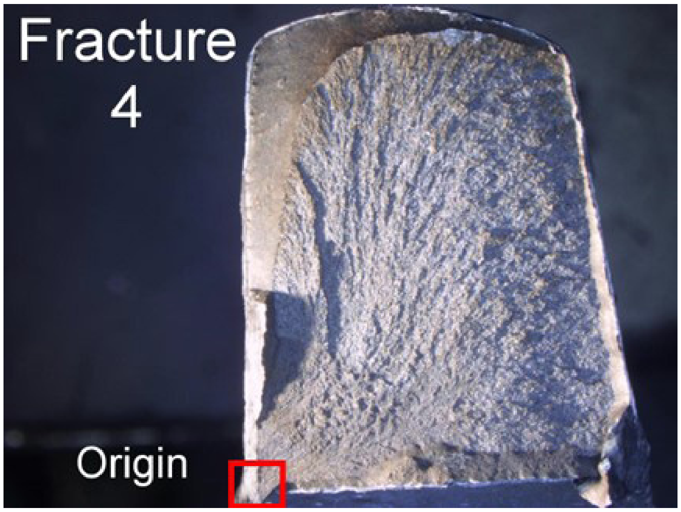

Figure 9
Shackle fracture 4, origin at the inner eye on the lower left.

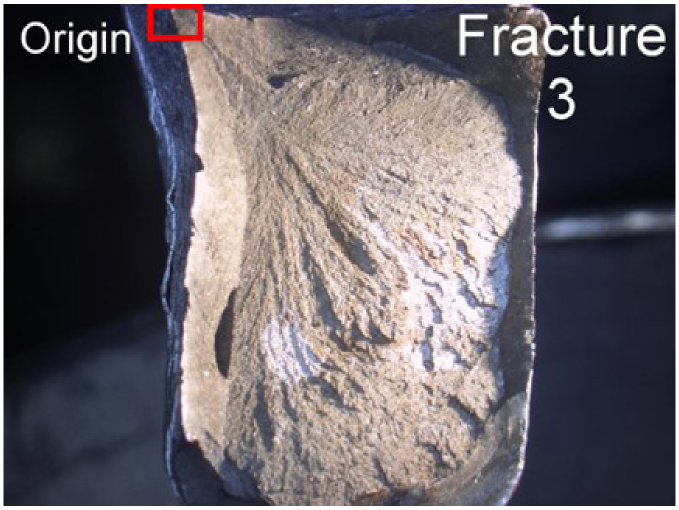

Figure 10
Shackle fracture 3, origin at the inner eye on the upper left.

The essence of the Company B working hypothesis was that these forging laps, coincidental with a trimming line (**Figures 11** and **12**), had created the critical crack size necessary for the crack to propagate through the arm under cold weather service conditions at Fracture 1 area shown in **Figure 8**. The forensic engineers concurred with the first part of the hypothesis, but disagreed that the service conditions were necessarily contributory, based on prior fracture mechanics and failure analysis experience. The low alloy 41Cr4 (5140) steel has a ductile/brittle transition temperature near -100°C (-148°F), and tempered martensite does not undergo this transition. The cold weather effect hypothesis was tested with a factorially designed series of experiments developed by the forensic engineers to quantify the effect of service temperature.

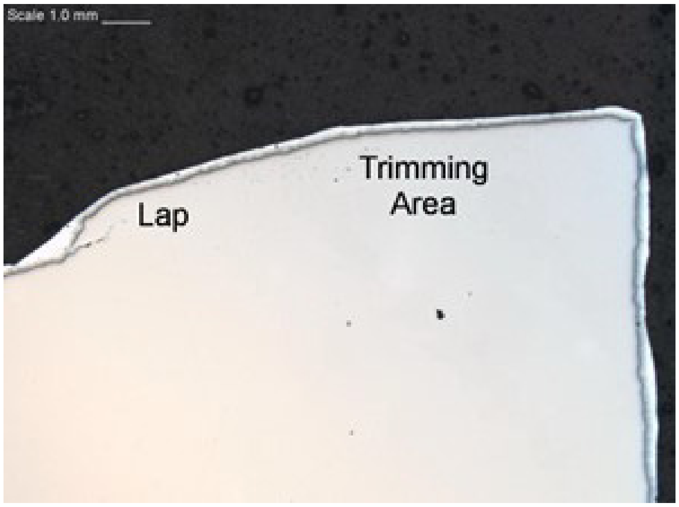

Figure 11
The trimming area with underlying lap.

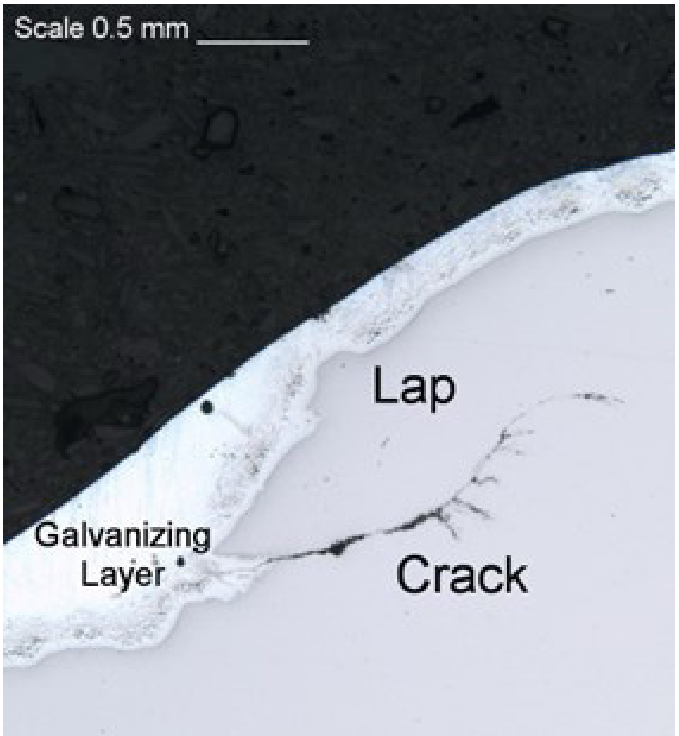

Figure 12
Magnified view of the crack in the trimming area.

Charpy Tests on Raw Material and Anchor Shackles

Charpy tests are employed to measure the notch toughness or impact strength of a metal, that is, its ability to absorb energy prior to failure. In this test, a notched specimen is broken by impact from a falling pendulum, and values are determined by the height the pendulum striker rises in the absence of a specimen versus the height the striker rises after the fracture of a specimen. The governing specifications for Charpy tests are ASTM A370-19e1 "Standard Test Methods and Definitions for Mechanical Testing of Steel Products"[4] and CAN/CSA G40.20 "General Requirements for Rolled or Welded Structural Quality Steel."[5]

Under CAN/CSA C83-96 Section 6.2.4 Energy Absorption/Toughness, the Charpy test criteria evaluate the raw material's conformance in Level 1 Energy Absorption, not the subsequent components, with the testing performed at -20°C and a minimum 20 Joules requirement to pass as Level 1 material.

Furthermore, ASTM E23-12c: "Standard Test Methods for Notched Bar Impact Testing of Metallic Materials"[6] clearly expresses in its Appendix XI that Charpy tests do not reflect actual service stress conditions. Charpy results are not an effective means of retroactively assessing a component once it has been placed in field service. Processed metal components become anisotropic — they have properties that depend on orientation as discussed in Hertzberg[7] and Hosford and Caddell[8].

Although it was clearly laid out as a "variable" of the raw material to be inspected prior to production rather than as an "attribute" inspected in a finished component, Company C attempted to verify the Charpy test behavior of 150 shackles taken from the utility company inventory using the tightened inspection format of Table A1 of Appendix A of CAN/CSA C83-96. A variation was discovered in the response at -20°C, in which some sample bars did not meet the specified minimum value of 20 Joules.

The variation appeared to be related to the location of the samples, taken from one of three places in the body of the shackle shown in **Figure 13**, with those in #2 central position testing significantly lower and not meeting the acceptance criteria. These are not the area where the shackle failed adjacent to the clevis pin hole, shown in

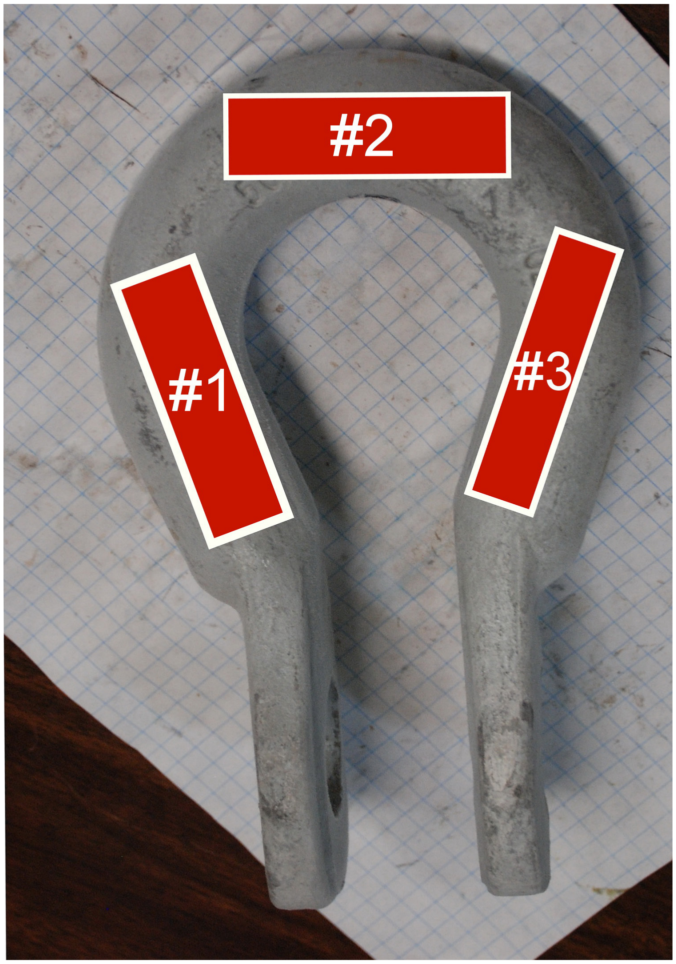

Figure 13
Locations of typical Charpy tests for Company C.

Figure 5. A summary of data from the Charpy tests is presented in **Figure 14**.

Place	Lower (J)	Upper (J)	Accept?
Position 1	21	27	Yes
Position 2	15	17	No
Position 3	21	27	Yes

Figure 14
Overview of Charpy testing results range by Company C.

Company C's series of tests further involved cutting cross-sections of the four portions of the arm adjacent to the pin and evaluating these for the presence of cracks/laps arising from the forging process. This was performed by Company B on contract. Six hundred specimens were mounted, polished, and examined under low power using an optical microscope.

There were seven cross-sections (4.67%) that showed internal cavities longer than 2.5 mm at a location 5 mm or less from the surface on the inner pin side. There were cracks longer than 1.5 mm at a position no more than 2 mm away from the critical area, and only 35 shackles possessed lap defects that could have been detected by magnetic particle inspection (MPI) methods, according to the authors of the Company B summary report.

At this point of the investigation, it appeared that the components' raw material had not met the minimum specified Charpy values for one group of specimen orientation. It became clear that there were cracks associated with lap defects, of which there should be none in an acceptable batch under the CAN/CSA C83-96 Table 3 requirements. This information confounded the owners because a clear decision on acceptance or rejection could not be made based solely on the summary prepared by Company B. A different approach was required to solve the puzzle, and the task was assigned to the forensic engineers.

Cold Temperature Shackle Tensile Testing

A statistically valid fit-for-purpose testing program[9,10] was designed by the author to evaluate a sample of the 2525 batch of shackles procured by the project manager from the European manufacturer but that had not entered service. The program design included the following elements:

1. Selection and design of a customized test method with factors and response functions chosen to emulate field service tension conditions;
2. Selection of a set of temperatures representing the winter extremes encountered by the product at the site in Northern Canada's high latitudes;
3. Procurement of specialized fixtures and a cold-environment stage for the tensile testing machines;
4. Procurement of a random sample batch 2525 shackles held in the utility's stock;
5. Capture of data and live analysis of shackle attributes during the tests; and
6. Post-test metallurgical analysis of shackle fracture surfaces (if these were created).

An additional phase consisting of metallographic specimen evaluation of the cross-sections of the shackles at the midpoint of the eye was instigated to compare and contrast these with results obtained independently by Company B.

The factorial design was chosen with two factors set at two levels, with response functions shown in **Figure 15**, to determine if these factors could explain the field behavior.

Experimental Factor	Low Level	High Level
Load	Reusability load	Breaking/max load
Temperature	-20 Celsius	-40 Celsius

Response Function	Measurement Units
Permanent deflection, nominal rated and maximum load	Percent
Yield strength in tension	MegaPascals
Breaking load in tension or maximun load borne	kiloNewtons
Elongation percent at failure	Percent
Reduction of area at failure	Percent
Mode of fracture (if failure occurs)	N/A descriptive
Time to facture (if failure occurs)	Minutes and seconds

Blocked Variable	Measurement Units
Crosshead speed of machine	mm per minute
Time held under load	Minutes
Shackle production batch	N/A descriptive

Figure 15
Factorial experiment design elements.

Figure 16
Samples as-received from Batch 2525 stock.

Twenty shackles were obtained from the utility's warehouse, and randomly assigned (**Figure 16**) reference identification numbers. The testing run sequence order was set from first to last, according to the size of a random number generated on a calculator, for each run of the factorial design. These shackles were placed into simulated cold temperature field service conditions, with similar parameters to the Company A room temperature tensile test assessments.

Tensile tests were performed by Company D in the special environmentally controlled chamber on an Instron universal test machine for the nominal rated load, and then on a SATEC universal test machine for the maximum load levels. Universal testing machines include electromechanical and hydraulic systems to perform static testing, including tensile, compression, bend, peel, tear, and other mechanical tests. The utility calculated that the maximum load on the shackles would be 127 kN, not including wind oscillation and other cyclic loads. The configurations are shown in **Figures 17** and **18**.

Figure 17
Environmental control stage on the Instron tensile test machine for rated load tests.

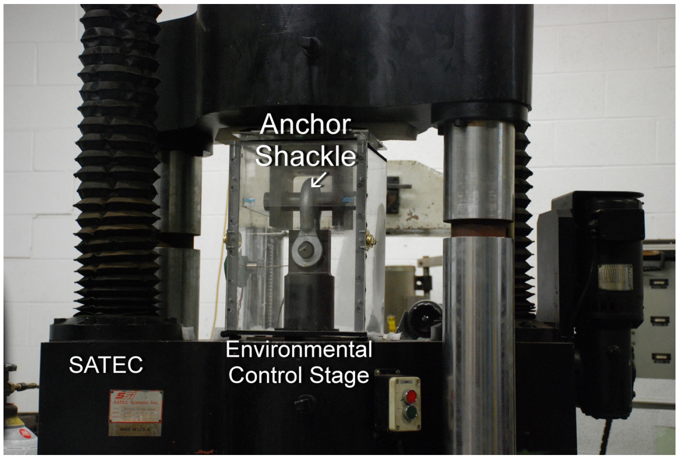

Figure 18
Tensile testing fixture with atmosphere control cabinet on the SATEC machine for maximum load tests.

With respect to a potential Daubert challenge, the hypothesis was tested using well-known techniques on widely owned tension testing equipment used throughout the industry with experimental design methods that are also well-known and employed. Tensile test results have error rates that derive from material property variability. The equipment is calibrated on a regular basis by the laboratories, according to international standards. Tensile testing has widespread acceptance within industry as a method of comparing and assessing material properties. Organized testing was first introduced by the railway companies. In 1901, the first standards were promulgated by the American Society for Testing and Materials (ASTM).

The first stage of mechanical testing consisted of temperature conditioning followed by a low-level load test. Specimens were cooled to the specified test temperature and held long enough to reach thermal equilibrium. Then, they were inserted into the Instron machine, and a pre-load of 0.7 kN was applied. The cross-head was then extended at a rate of 40 mm/minute up to a load of 374 kN (the reusability load) where it was held for 5 minutes before the load was released. The reusability load level is defined on page 319 of the CSA Standard — 374 kN compared to the 440 kN rating of a Number 9 Anchor Shackle.

For the second stage of mechanical testing, the shackle was then conditioned again at the test temperature and moved to the SATEC test machine. The specimen was loaded at a rate of 8 mm/minute to a load of 440 kN, where it was held for 5 minutes. The specimen was loaded at the same strain rate to a load of 530 kN to 575 kN, at which point the fixture pins began deflecting, and the experiments were terminated.

Results of the load testing showed that there were no temperature effects on tensile performance in fitness-for-purpose testing (**Figure 19**). At -40°C, which is a typical minimum winter temperature for Northern Canada, none of the test shackles fractured. As seen in the next section, 1-mm lap cracks were subsequently found to be present on the inboard edges — a little more than 5 mm from the critical area. Despite the presence of these defect-like indications, through-cracks neither developed from the lap positions nor originated from the critical corner when subjected to applied tensile forces up to 575 kN, which is more than 13% above the maximum rated shackle strength of 506 kN.

Factor Levels	Coded Shackles	Factor Details	Response
Low, low	1G, 1A, 2C, 1E, 2B	374 kN reusability load, -20 C	No fractures initiated
High, low	1G, 1A, 2C, 1E, 2B	Max. 575 kN load, -20 C	No fractures initiated
Low, high	1F, 1C, 1I, 1D, 2E	374 kN reusability load, -40 C	No fractures initiated
High, high	1F, 1C, 1I, 1D, 2E	Max. 575 kN load, -40 C	No fractures initiated

Figure 19
Results at factor level settings for fracture initiation.

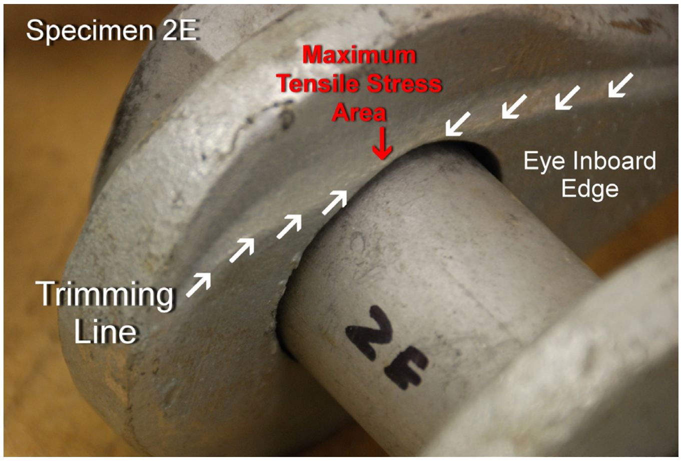

Figure 20
The poor intersection of the trimming line on Specimen 2E.

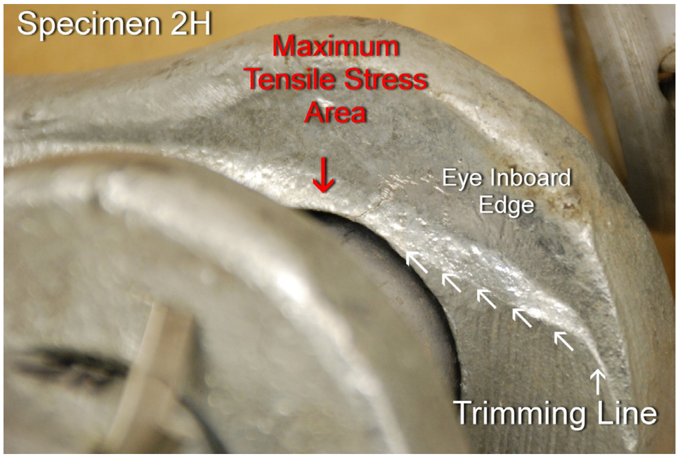

Figure 21
Example of poor trimming line intersection on Specimen 2H.

Illustrations of Poor Trimming Line Geometry

As previously described, the shackles must be trimmed after forging to remove excess flash left over from the forging process. The working hypothesis was that fracture initiation from stress concentrators that develop when the trim line coincides with the edge of the eye — the area of highest stress when the shackle is under load. In field service conditions, these local conditions may create the circumstances for crack propagation and failure.

To illustrate the trimming issue, **Figures 20** and **21** show the trimming line meeting the edge of the eye on specimens 2E and 2H.

Post-Test Sectioning and Metallography

At Company E, the group of 10 shackles were sectioned in a manner similar to the European laboratory, at the midpoint of the eye (**Figure 22**), to inspect the critical area for the presence of lap defects arising from the post-forging trimming process.

Of 40 cross-sectional specimens from 10 shackles, eight were enumerated with laps in the plane of center of the eye, with two laps near the critical area 5 mm from

Figure 22
Specimens cut and polished for metallographic assessment of the critical area.

the eye edge on the inboard side of the shackle arm. These ranged from 0.2 mm long by 0.25 mm wide to 1.8 mm long and 0.6 mm wide, which were comparable to those found by Company B. These are Class B defects (very serious), according to CAN/CSA C83.115-96.

Seven of the laps were located along the inboard edge of an arm, more than 8 mm away from the critical corner. The cross-section of 2E-A was unremarkable under low-power microscope. An 0.8-mm-long by 0.2-mm-wide crack in 2E-B was observed around the midpoint, as shown in the figures. The examination of mounted, polished, and etched specimens using a metallograph (metallurgical microscope) showed that these laps had not opened during the tensile testing processes, such that no through-cracks were observed in any of the 10-shackle sample. Representative images are shown in **Figures 23** through **29**.

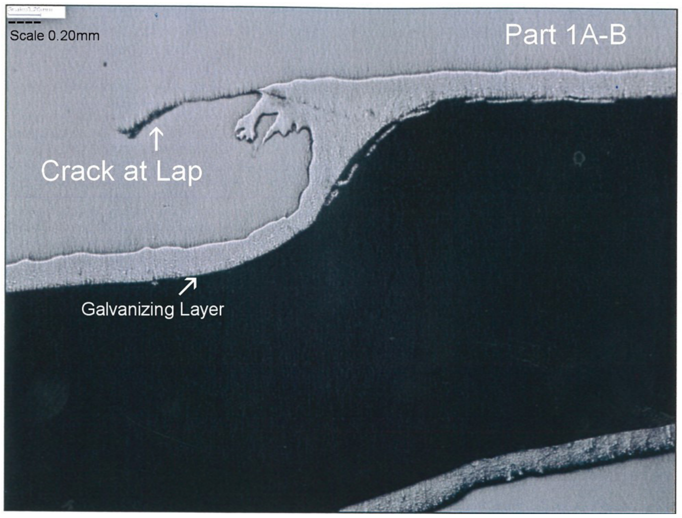

Figure 23
Polished cross-section showing crack at lap in Part 1A-B.

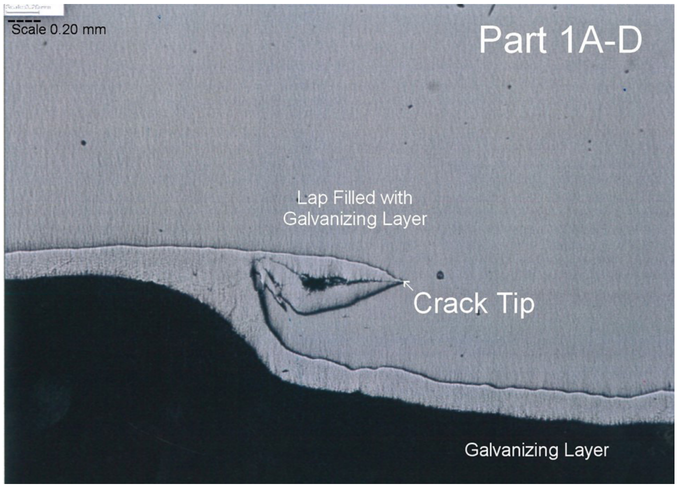

Figure 24
Polished cross-section showing crack tip in Part 1A-D.

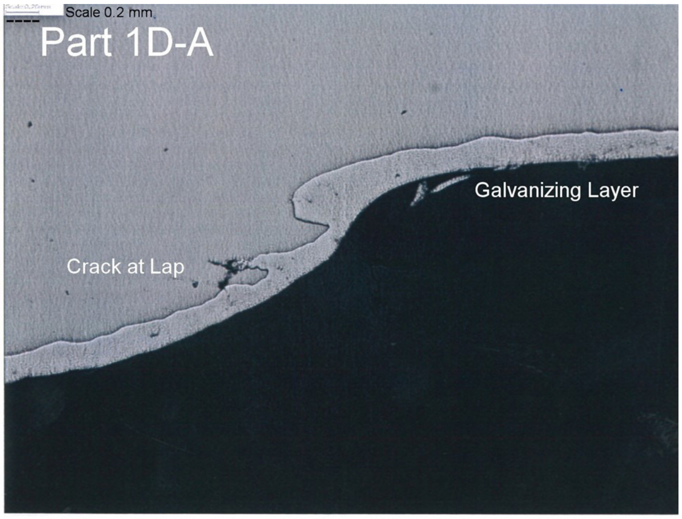

Figure 25
Polished cross-section showing crack at lap in Part 1D-A.

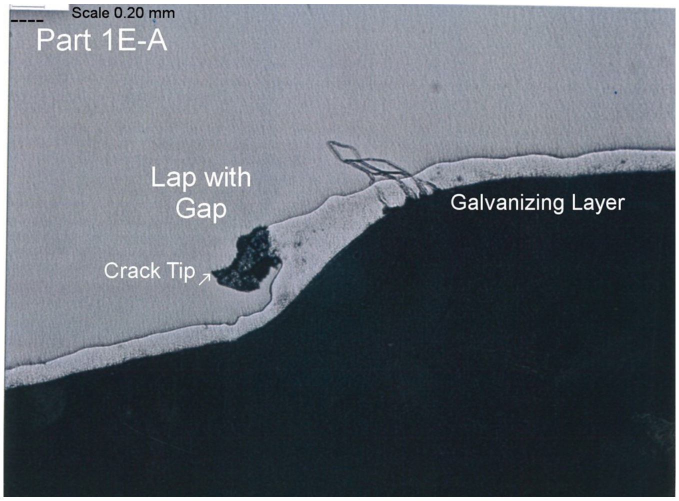

Figure 26
Polished cross-section showing crack tip by gap at lap in Part 1E-A.

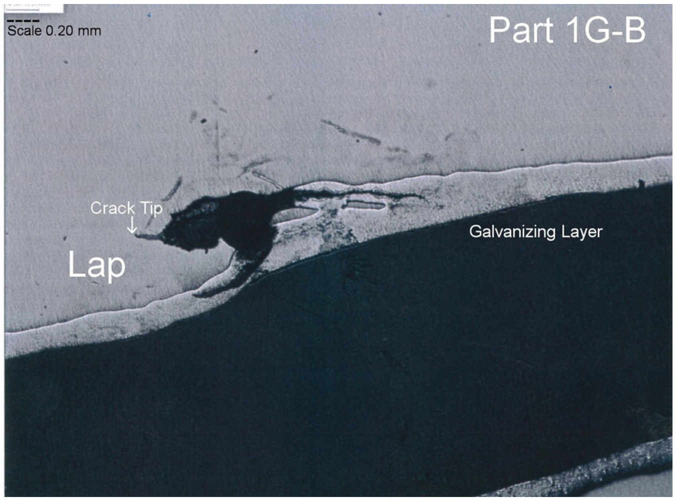

Figure 27
Polished cross-section showing crack tip at lap in Part 1G-B.

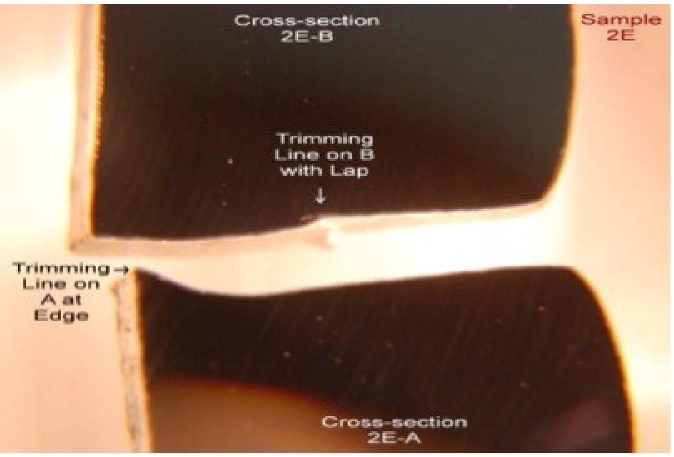

Figure 28
Mounted and polished cross-section of 2E-B with laps.

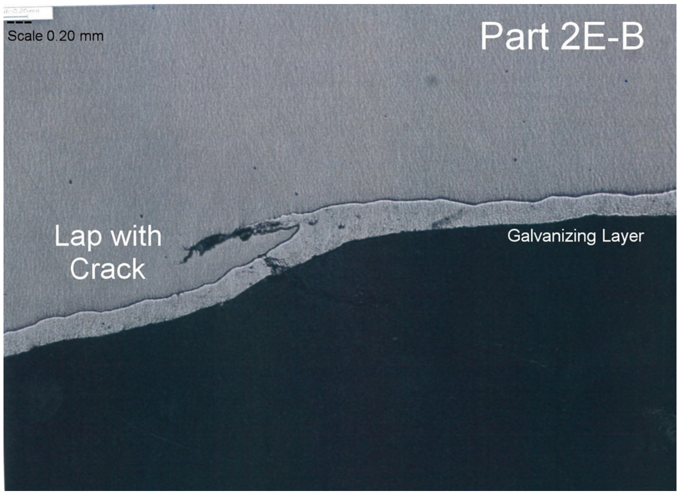

Figure 29
Polished cross-section showing the lap with crack on Part 2E-B.

Discussion

Validity of Observations Established by Representative Statistical Sampling

Through careful factorial design and random sampling, observations made on the random sample group were reasonably extrapolated to be representative of the whole population of shackles and showed results comparable to those in other assessments. Most importantly, the tests were able to replicate extreme loading conditions and temperatures that the shackles would experience in field service.

Insights Confirmed and Gained from the Shackle Assessment

The shackle batch evaluation programs have revealed evidence of conformance issues with Class B defects at frequency levels measured to be higher than the 1% limit in CAN/CSA C83-96 (2011), confirming the following insights:

a. The effects of trimming during the manufacturing process, located at the critical area of the shackle eye, disguised forging lap defects there;

b. Galvanizing in a subsequent step prevented detection of surface cracks by non-destructive techniques, such as magnetic particle inspection (MPI) or dye penetrant inspection (PTI); and

c. Company B identified the trimming line adjacent to the crack origin in the field failure shackle, possibly on both sides, as a factor in the development of the crack that led to the field failure of the anchor shackle.

The assessment supported a new insight that a statistically significant percentage of the shackles in Batch 2525 have forging lap defects, but few cracks are found at the critical eye intersection.

Forging Defects in Metal Products

Forging defects are well known to be a source of concern in components, such as hooks used for lifting materials. Laps introduce stress concentrations and redistribute loads under service conditions in a way that may not have been anticipated during the original design process.

Generally, a manufacturing process should have an inherent ability to avoid the creation of forging laps. If not, active factory quality control processes should be set to detect them and thus allow the manufacturer to remove them or mitigate their effect in a subsequent operation. In this particular instance, the Company A forging process created the laps in a tempered martensite microstructure sensitive to cracks, but did not remove them during subsequent trimming. Laps were then obscured with a galvanizing process. The forging lap crack acts as a stress concentrator in tempered martensite, magnifying the localized stress to a magnitude well beyond the nominal yield stress.

This combination rendered the quality of the shackles unacceptable per the AQL terms of CSA C83.115-96. They should not have entered service as part of an important transmission line assembly if the CSA C83.115-96 criteria had been the sole standard applied to judge their suitability. The anchor shackles would not comply with the letter of the standard.

Critical Defect Characteristics

Laps and associated cracks were observed in a statistically significant proportion of the sample of shackles evaluated by the forensic engineers (and within the samples evaluated by the European laboratory); however, these were in positions away from the critical region. The designed experiments could not induce fractures when overstressing the shackles under extreme low temperature conditions even in the presence of these defects very close to the critical locations.

The forensic engineering investigation showed that the position of the lap relative to the critical area was the most significant factor when assessing its potential effect on field performance. Unless a forging lap crack intersects exactly with the critical eye region under the highest tensile stress, the pre-condition for induction of a shackle arm failure under field loading is not met. Cracks at the laps in the shackles did not propagate across the arm at the eye to break the shackle when loaded to 575 kN at -40°C.

Probability of the Presence of Forging Lap Cracks

The population of shackles produced for the project likely contained an unacceptably high level (approximately 125 of 2,600, about 5%, compared to the 1% allowable limit) of actual forging lap defects that would not meet CSA C83.115-96 conformance requirements. The probability of a shackle possessing a forging lap crack at the critical juncture was a fraction of that because of the reduced odds of the coincidental geometry in which a forging lap intersects the critical stress area.

The shackles' tensile behavior was shown to be insensitive to very low temperatures. However, the presence of forging laps at a critical area that led to a functional failure event in the field (a Class A Critical unacceptable defect according to the CSA C83.115-96 criteria) disqualified the entire shackle product Batch 2525 as unsuitable for service in critical transmission line infrastructure. The situation was exacerbated by the demonstrated fact that the defects could not be detected retroactively with nondestructive testing techniques.

Ineffective Analysis through Charpy Testing

Charpy testing alone could not distinguish the defect and was an inappropriate screening tool. That method is best used as a quality tool to qualify raw materials, rather than to retroactively approve components — an aspect overlooked by Company C. The forging process changes the fracture toughness of the steel by changing its microstructure permanently, and creates variability within the component by straining the metal such that the Charpy results are skewed when compared to the original material.

Factorial Design Experimental Program Determined the Root Cause

In contrast, the factorially designed program tests subjectively qualified the shackles for use in transmission service, independent of the CSA C83.115-96 criteria, with the explicit restriction of a shackle being redundant within the tower array configuration. The forensic engineer's experimental design evaluated the fault and then tested it with a relevant simulation that could be extrapolated to the set of shackles in the batch. This allowed the root cause to be put into perspective.

Summary

Company A's Number 9 anchor shackle manufacturing process created a technical issue, the magnitude of which could not be resolved by visual inspections on components of the transmission line once a fracture incident had occurred. The utility and Company C ineffectively attempted to requalify the components by retroactively applying one of the raw material acceptance criteria; however, passing a Level 1 Charpy toughness test generally does not replicate field service conditions. The findings of their examination only served to confuse whether the components should have been accepted in the first instance, when cross-sections of the shackles found cracks that were not permitted by the governing standard.

To determine the scope of the problem and to reassure the owner of the fit-for-purpose safety of the Number 9 anchor shackles on the transmission line, it was necessary to carefully design a tensile test to replicate the most extreme service conditions and then apply statistical techniques.

Epilogue

The technical analysis of the root cause by the forensic engineers was employed by the utility's operations group to focus its shackle removal and replacement plan by the project management firm to refine the procurement specification for shackles. To greatly reduce the opportunities for additional field fracture development while avoiding the high cost of full replacement, the shackle arrays were theoretically checked for redundancy. Those in primary load-carrying positions were selected for removal and replacement. The opinions and results were cited in the discussions with the manufacturer about compensation for the replacement program costs prior to litigation proceedings.

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References

1. For more information on applied quality theory in manufacturing practice, visit American Society for Quality at ASQ.org, and see https://asq.org/quality-resources/quality-glossary/.

2. *Communication and Power Line Hardware*, CAN/CSA C83-96 (2011), Canadian Standards Association, Etobicoke, ON, Canada, 2011.

3. *Communication and Power Line Hardware: Appendix J*, CAN/CSA 83.115-96 Shackles, Canadian Standards Association, Etobicoke, ON, Canada, 2011.

4. *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*, ASTM A370-19e1, ASTM, West Conshohocken, PA, USA, 2019.

5. *General Requirements for Rolled or Welded Structural Quality Steel*, CAN/CSA G40.20, Canadian Standards Association, Etobicoke, ON, Canada, 1998.

6. *Standard Test Methods for Notched Bar Impact Testing of Metallic Materials*, ASTM E23-12c, ASTM, West Conshohocken, PA, USA, 2012.

7. Richard W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*. Hoboken, NJ, USA: Wiley, 1976, pp 327-335.

8. William F. Hosford and Robert M. Caddell, *Metal Forming: Mechanics and Metallurgy Second Edition*. USA: Prentice Hall, 1993, pp 244-303.

9. George E. P. Box, J. Stuart Hunter and William G. Hunter, *Statistics for Experimenters: Design, Innovation and Discovery*. Hoboken, NJ, USA: Wiley, 2005.

10. Bert Gunter and Daniel Coleman., *A DOE Handbook: A Simple Approach to Basic Statistical Design of Experiments*. USA: CreateSpace, 2014.