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FE Investigation of Maintenance and Operational Factors Contributing to the Collapse of a Crane Boom

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Abstract

During the coating of a natural gas pipeline, all 14 bolts securing the pedestal of a crane boom to a truck bed failed, causing the boom to fall and strike a worker in the head. The bolts exhibited excessive corrosion indicative of exposure to a harsh corrosive environment prior to the failure. Review of provided documents revealed that the crane was kept in an uncovered yard for two years. Afterward, it was rented to petrochemical companies for use in heavy oil and gas industrial environments. The fracture surfaces of the bolts revealed signs of excessive fatigue, which were determined to be caused by loadings that the previous renters of the crane had subjected it to. Bolt fatigue drastically reduced their strength, allowing them to fail under loads well below the recommended load capacity of the crane. Maintenance records indicated that the lessor failed to perform adequate inspection of the crane, allowing bolt corrosion and fatigue to go unnoticed. Had proper inspections and maintenance instructions been provided and performed, the incident would not have occurred.

Keywords

Fatigue, heat treatment for fasteners, hydrogen embrittlement, crane boom, periodic inspections, forensic engineering

Case Background

A pipeline maintenance company was in the process of re-coating an excavated natural gas pipeline. Discovery documents describe their recoating procedure as follows: A heating ring is lowered onto the pipe via a crane and latched in place. The ring heats the pipe and is then relocated farther down the pipeline. A coating ring is then attached to the hot pipe segment and applies a spray coating to the area. A crew is typically able to repeat this procedure between 45 to 65 times per day.

At the time of the incident, the crew had lowered a heating ring onto the pipeline and heated the pipeline to the required temperature. One of the workers then walked over to the heating ring to detach it so it could then be taken off of the pipe. After unlatching the heating ring from the pipeline, the worker moved away and signaled the crane boom operator to lift the unlatched ring. Suddenly and unexpectedly, all 14 bolts securing the subject boom to the truck body failed, causing the crane boom to collapse, striking the worker on the head/back, and resulting in a traumatic brain injury. As a result of this incident, litigation was filed against the equipment lessor, the crane manufacturer, and the bolt manufacturer. The authors were retained in order to investigate the mode of failure/design of the crane and assess the quality of the preventive maintenance performed by the lessor.

Subject Crane Boom

The subject crane boom was sold to an oil and gas equipment lessor on December 30, 2014. It was a hydraulic crane rated to have a maximum lifting capacity of 12,000 pounds. According to company documents, it was reportedly initially mounted to a truck body in 2016; however, the exact date of installation was not recorded. For all of 2015 and part of 2016 (between purchase date and installation date), the subject crane and the 14 provided attachment bolts were stored in an outdoor, unprotected storage yard. After installation, the crane was moved to another outdoor yard where it was stored for an undisclosed amount of time before it was first leased out.

After it was mounted to the truck body, the crane was reportedly used for more than two years and logged a total of 1,412 hours by the time the pipeline maintenance company acquired it. Provided records indicated that the

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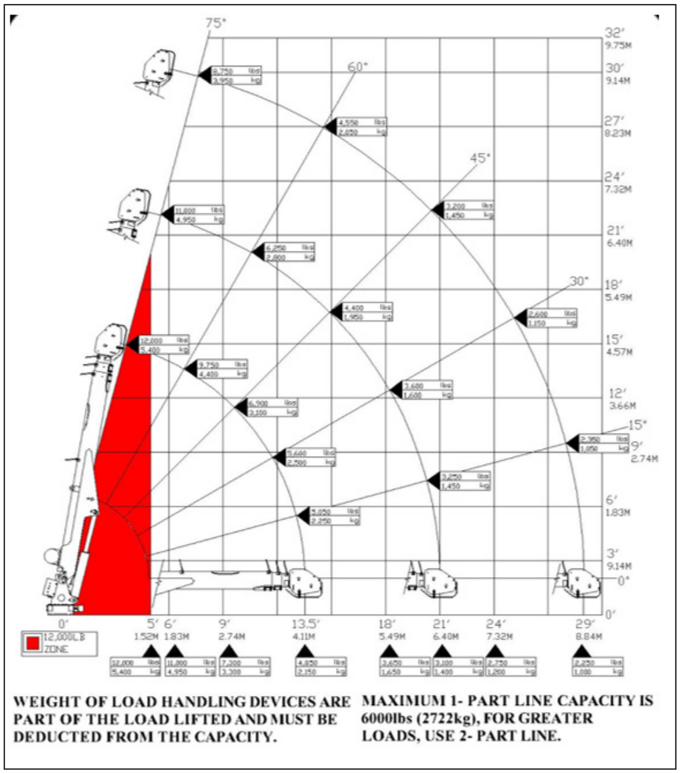
crane was previously rented out five times for projects in several oil and gas work sites, including, but not limited to, Brownsville, Texas; Ellenboro, West Virginia; Midland, Texas; Yukon, Oklahoma; and Hollidaysburg, Pennsylvania.

These locations are known areas of heavy shale oil activity, where equipment is regularly exposed to corrosive liquids and pushed to their limit. It is unknown if the crane boom was subjected to misuse and/or abuse prior to its acquisition by the final lessee. Inspection documentation from the lessor was noted to be inadequate and based on cursory visual inspections. As a result, any damage that would have occurred to the bolts due to misuse was not noted. Other than the lessor testifying to the fact that they had no idea how the equipment was used (or if it was misused), there were no additional discovery documents available to ascertain previous excessive loading or loading frequency.

The crane was last recorded to have undergone full service on August 15, 2019 by the equipment lessor. The maintenance company acquired the crane on or around November 14, 2019, and used it at the job site between 45 to 60 days prior to the incident. No records of any other inspection or maintenance between the last full service and the date of incident were available. A 24-inch induction heating ring was used with the subject crane at the time of the incident for pre-heating of the finished pipe joint to prepare for the epoxy coating process (**Figure 1**).

Inspection of the crane revealed that, at the time of the incident, the crane was at a 35° angle and was extended approximately 18.27 feet (219.25 inches). According to the crane's load chart, the crane boom's max load capacity at this angle was over 3,600 pounds (**Figure 2**). Testimony from the crane operator and workers on site at the time of the incident stated that the crane failed as soon as the heating ring began to be lifted. The crane operator also testified that he was lifting the heating ring at a slow speed and that it was no longer connected to the pipe.

Figure 1
The collapsed crane boom at the site of the incident.



WEIGHT OF LOAD HANDLING DEVICES ARE PART OF THE LOAD LIFTED AND MUST BE DEDUCTED FROM THE CAPACITY.

MAXIMUM 1- PART LINE CAPACITY IS 6000lbs (2722kg), FOR GREATER LOADS, USE 2- PART LINE.

Figure 2
Chart showing the load capacity of the crane boom at different extension lengths and orientations.

The separation at the connection between the rotation base and the pedestal is shown in **Figure 3**. A total of 14 bolts were utilized to affix the crane pedestal to the truck body. All 14 of the pedestal bolts were recovered and labeled in accordance with the identification numbers in the crane's owner's manual (**Figure 4**). According to the owner's manual, these bolts were $^5/_8$ inch-11 × 3-$^1/_2$ inch SAE J429 Grade 8 Hex cap fasteners with a 5µm thick yellow zinc coating (i.e., a coating consisting of chromate applied over a zinc coating). This coating was applied via an electroplating process. These fasteners were noted to have a minimum proof strength of 120,000 lbs/in^2 (psi) and an ultimate tensile strength of 150,000 psi.

At the time of the forensic examination, 12 of the failed bolts were still inside the pedestal while the remaining two bolts were found lying on the truck body.

All of the examined bolts exhibited a lack of yellow

Figure 3
Overall and close-up views of the bolt circle where the failed bolts were attached.

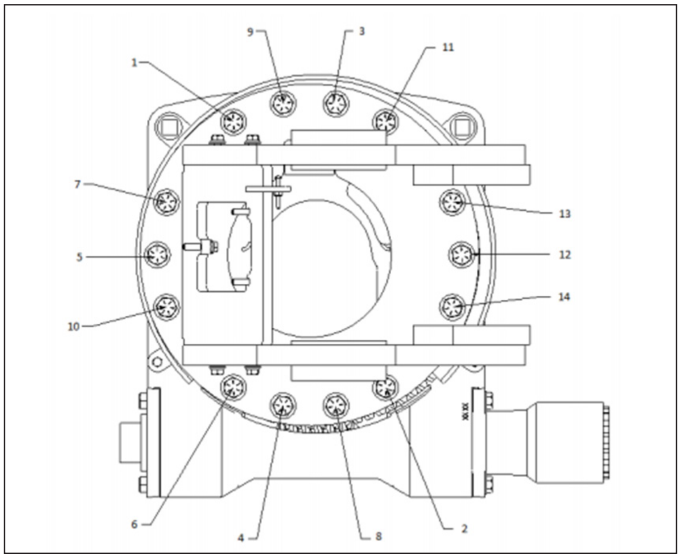


Figure 4
Diagram of the crane pedestal with each of the 14 bolts labeled with numbers 1 through 14. Note that bolts 7, 5, and 10 are located on the far side (rear) of the pedestal.

zinc on their heads, and a number of the bolts displayed significant depletion of this coating on the bolt shank and threads (**Figure 5**). It is likely that the yellow zinc coating was depleted from the bolt heads over a long period of exposure to water or other corrosive mediums while these same corrosive mediums stagnated in the notches and bolt holes, allowing for the coating on the body of the bolt to

Figure 5
Heavily oxidized (rusted) surface of bolt #9, displaying iron oxide and traces of the chromate and zinc galvanic coating (highlighted by the white arrows).

be removed and result in the corrosion of the bolt shank and threads. While a small amount of corrosion was noted on the fracture surfaces of some of the bolts (**Figures 6** and **7**), comparison with extensive corrosion noted on the exterior surface of the bolts (**Figure 5**) indicates that this corrosion likely occurred following the failure as the fracture surface was exposed to four days of snowfall before the bolts were retrieved during the authors' inspection.

A common fracture pattern noticed amongst the failed bolts was the presence of area (A), having features consistent with fatigue, followed by an intermediate region (B) with rough, parallel crack arrest marks (indicative of particularly low cycle fatigue), and finally a region (C) indicative of fast fracture through an inclined fracture plane (shear lip), as shown in **Figure 8**.

Figure 6
One of the failed bolts, showing a metallic
yellow coating characteristic of yellow zinc.

Figure 7
Bolts 7, 5, and 10 — still in their bores at the
time of inspection. Note the severity of corrosion.

According to the owner's manual, the bolts are required to be torqued at 220 pounds-foot when dry and 170 pounds-foot when oiled. If bolts are overloaded in an amount exceeding the load stated in the load chart, then the bolts may become damaged and decrease the overall strength of the bolt. Examination of the bolt threads showed no signs of deformation consistent with overtorquing. In addition, red threadlocker (an adhesive applied to bolt threads to prevent loosening) was found in most of the bolt holes and around the bores. In the absence of any documentation that would indicate the bolts were torqued beyond their recommended level, in addition to the absence of any physical witness marks in the form of thread-stripping, the overtorquing of the bolts as a potential mechanism for their failure was overruled.

Other than the failed pedestal bolts, the only observed signs of damage were on top of the heating ring, the traveling block (a device consisting of the crane's hook and sheave pulley), the spreader bar (a beam that is attached to the crane's hook and distributes the load between two or more points), and minor damage to the rigging. This damage was concluded to have occurred as a result of the crane boom falling and striking the pipeline following the failure of the pedestal bolts.

Hypotheses for Failure

Bolts are known to fail in a variety of modes, yet the

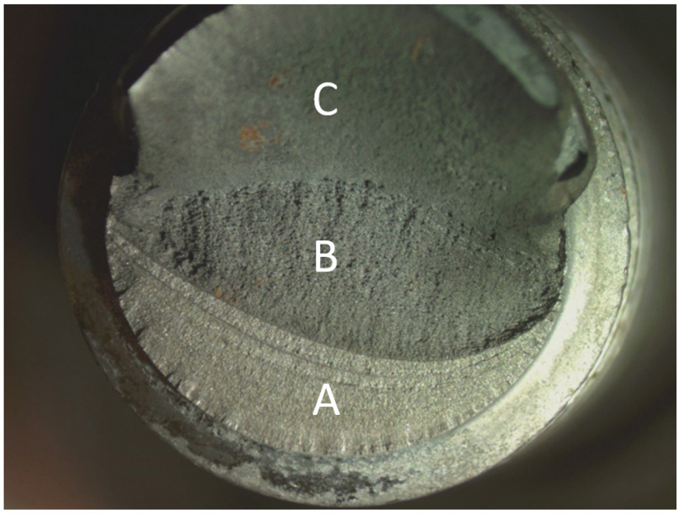


Figure 8
Fracture regions observed in a typical failed
bolt fracture surface: A (fatigue beach marks),
B (low-cycle crack arrest marks), and C (final sudden fracture).

most documented failure modes are overload and fatigue[1]. Overload failure is the ductile or brittle failure of a material that occurs when the stress exceeds the material's strength. While all material failures could be argued to occur in this manner, the term "overload" generally refers to instances where the applied stress exceeds the nominal strength of the material as considered in the design stage — either through misuse of the equipment, improper design, or improper material selection. In threaded fasteners, overload typically occurs when tension, shear, bending, and/or tortional forces exceed the nominal strength of the overall material cross section.

Fatigue is a failure mode that is characterized by the initiation and propagation of cracks within a material over time under the action of cyclical loading[1,2]. As the load cycles continue, the fatigue cracks progress further through the material's cross section, increasing the stress placed upon the remaining cross section. Eventually, the applied stress exceeds the material's nominal strength, and the remaining cross section of material suffers from an overload failure. The two stages of fatigue failure prior to the final fracture are shown in **Figure 9**.

Fatigue failures are typically characterized by markings such as beach marks, striation marks, and ratchet marks. Beach marks are elliptical or semi-circular macroscopic markings that are indicative of crack progression followed by periods of serve interruption and are seen as one of the primary indicators of fatigue. Beach marks typically radiate out from crack initiation sites. Striation marks are similar to beach marks yet represent each individual cycle of loading. As such, they are very small and cannot be observed macroscopically[1]. Ratchet marks are small step-like features caused by the overlap of multiple separately initiated fatigue cracking regions[3].

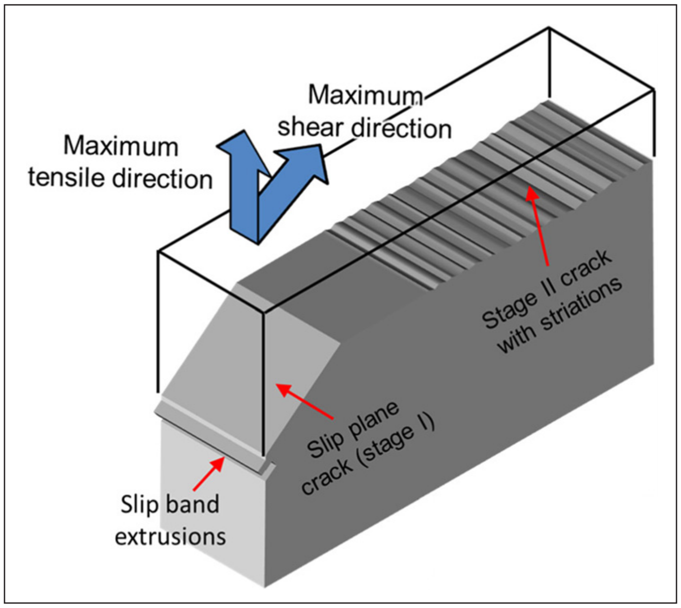


Figure 9
Schematic showing crack initiation (Stage I) and crack propagation (Stage II) of an advancing fatigue crack[5].

These separate fatigue initiation sites can be caused by stress concentration factors such as inclusions or corrosion pitting[1]. The manner in which fatigue occurs depends upon the rate and intensity of the cyclic loading. High cycle fatigue involves low-amplitude cyclic loads applied over an extended period of service. Elastic deformation of the material occurs under such conditions, resulting in the slow expansion of existing cracks or the creation of new ones. As such, high cycle fatigue exhibits very fine striations and beach marks. Conversely, low cycle fatigue involves high-amplitude loads applied over a short period of service. The higher stress amplitude experienced by the material results in local plastic deformation ahead of the crack front, which results in more extensive cracking. This can be seen by the larger, sharper striations and further displaced beach marks[4]. It is also important to note that fatigue is considered to be one of the most common mechanisms of failure in threaded fasteners, such as the bolts at issue[6].

Based on the above concepts, two competing hypotheses for failure of the bolts were developed. One hypothesis postulated that the heating ring may have not been properly detached, the crane could have been pulling on the heating ring while it was still attached to the 20-inch diameter pipeline, causing the bolts to experience an overload failure. Another hypothesis postulated that failure of the bolts occurred due to progressive fatigue fracture of the bolts as a result of combined environmentally induced embrittlement of the bolts and the cyclical loading experienced during the day-to-day operation of the crane.

The heat ring being lifted by the crane boom was reported to have weighed between 400 and 500 pounds, significantly below (12% to 14%) the maximum load capacity of the crane as specified by the crane's load chart for the specific crane boom length and orientation at the time of failure. These heating rings are designed to drop down over a pipe and close around the pipe via a light clamp at the bottom of the pipe, as shown in **Figure 10**.

According to a report by the crane manufacturer as well as the manufacturer of the heating ring, this clamp was not designed to carry any loads. The clamp on the

Figure 10
Images of the heating ring, displaying no apparent signs of damage to the ring itself or the securement clamp (circled in white).

heating ring would have failed, or, at a minimum, displayed clear signs of damage if the heating ring had been used to raise any section of the pipe. Visual examination of the heating ring showed no signs of damage to either the clamp joint or the bottom portion of the heating ring itself, indicating that the crane boom was not overloaded through improper detachment of the heating ring. This conclusion was further corroborated by the failure analysis reports of the crane boom manufacturer and bolt manufacturer, both of which came to the conclusion that the heating ring was undamaged, and an overload failure did not occur.

The first hypothesis for failure can thus be ruled out based on the aforementioned information, which shows that the pedestal bolts did not fail purely as a result of the imposed loading.

Failed Bolts Fractography

Optical microscopy and scanning electron microscopy (SEM) were performed on the 14 failed pedestal bolts to examine their fracture surfaces. As previously mentioned, examination of the bolts revealed that at least half displayed fracture surfaces with three distinct regions. Beginning from the exterior surface of the bolts (at the bottom of the fracture surfaces shown in **Figure 11**) is a region displaying distinct beach marks (B), with a number of bolts possessing ratchet marks (R), signifying multiple fatigue crack origins. There is a marked transition to the intermediate region, displaying rough, parallel, crack arrest marks (C), indicative of very low-cycle fatigue. Finally, there is a steep transition to a “fast fracture” region where final failure occurred through an inclined shear fracture plane (S). Macroscopic and SEM images of a number of the bolts’

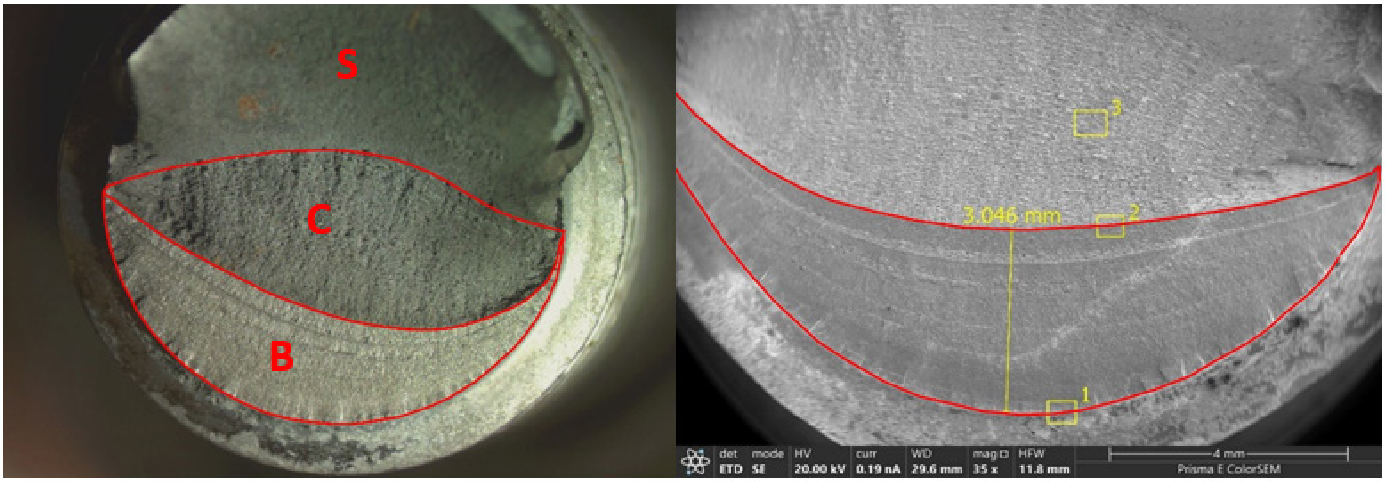


Figure 11
Fracture surface of Bolt #6, displaying three distinct regions. The presence of beach marks (B), parallel crack arrest marks (C), and a shear lip (S), are noted on the figure (left). A closer view of the beach marks and the parallel crack arrest marks are shown in the image to the right.

cross sections are shown in **Figures 11** through **15**. Features indicative of fatigue, such as beach marks (B), crack arrest marks (C), and ratchet marks (R), are marked on the first two sets of images. The remaining bolts were noted to exhibit large regions of parallel crack arrest marks and a lack of beach marks or patterns indicative of pure cleavage (**Figures 16** and **17**). These pronounced marks are due to the quicker fatigue fracture progression as a result of higher stresses experienced.

Figures 11 through **17** show that many of the bolts experienced regions of fatigue failure as evidenced by classical witness marks such as beach marks and ratchet marks. Some of these bolts also displayed the presence of long-term fatigue failure, evidenced by the presence of beach marks having highly differentiable corrosion texture (**Figures 14** and **15**). The combined presence of classical beach marks with highly differentiable corrosion bands suggest stress corrosion cracking as a mechanism that contributed to the failure of the subject bolts. The fracture surfaces observed on the 14 bolts also proved to be similar in nature to those that have been reported in literature[7,8] (**Figure 18**). Based upon this evidence, fatigue failure was identified as the primary mode of failure of the subject bolts.

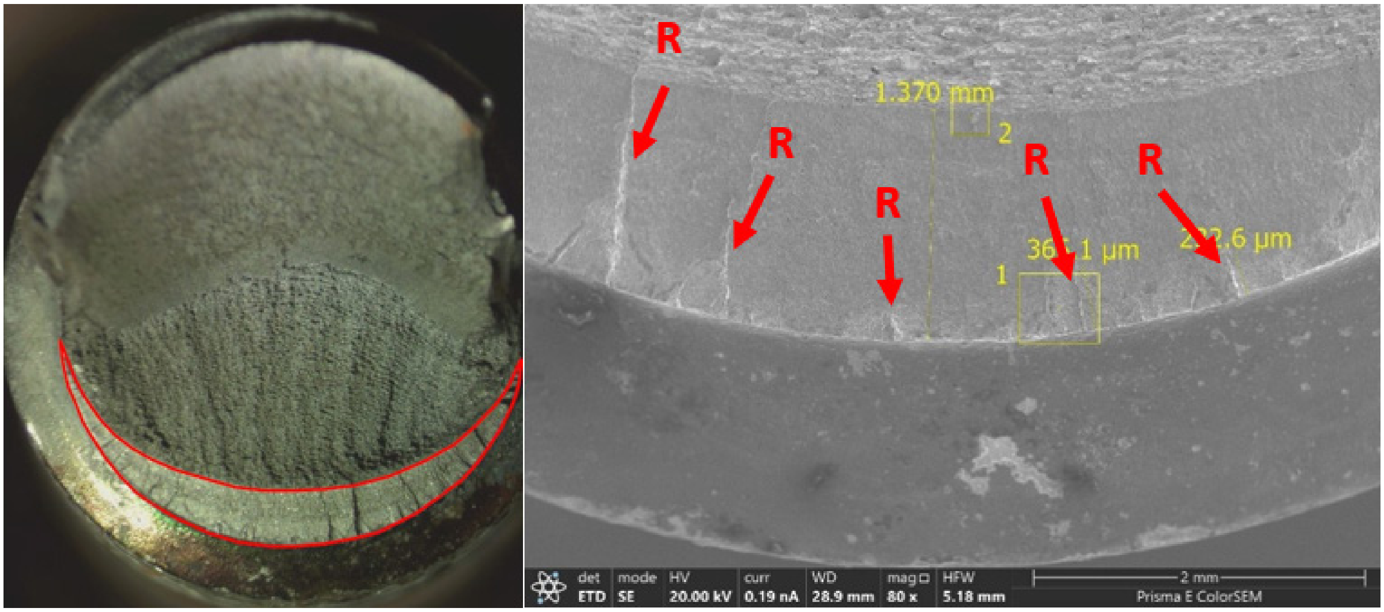


Figure 12
Fracture surface of Bolt #1, displaying crack arrest marks reaching up to the middle of the cross section. A smooth, outer zone with beach marks can be seen, signifying fatigue (left image). The fatigue region of this bolt also displays a number of ratchet marks, highlighted by the red arrows (right image).

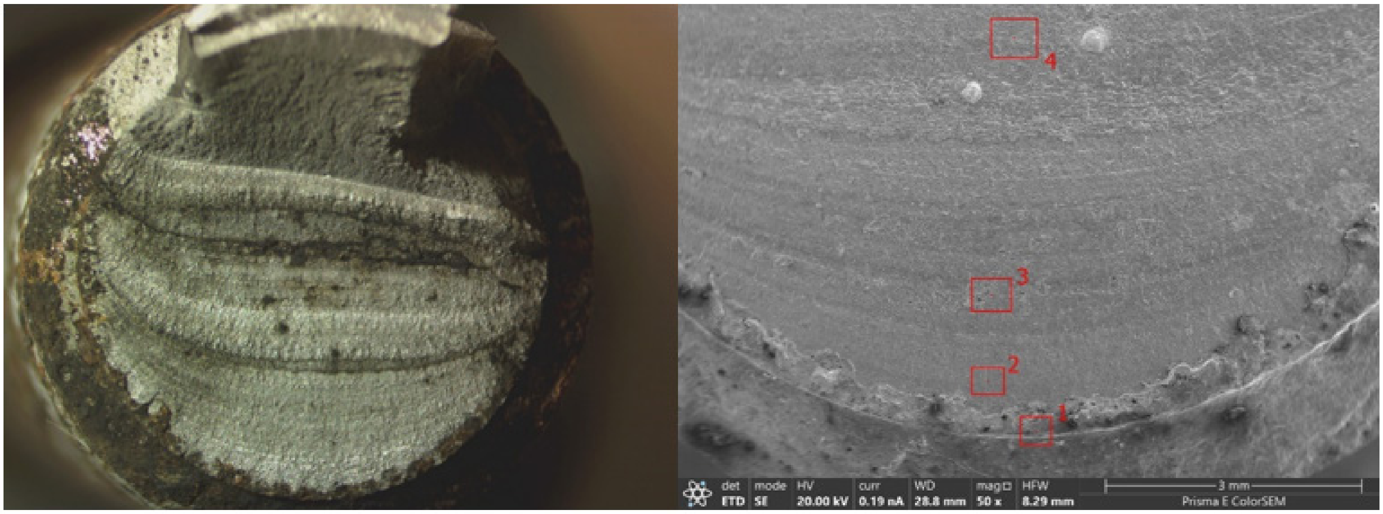


Figure 13
Fracture surface of Bolt #10, displaying a significantly large region of beach marks that extend through a majority of the bolt cross section.

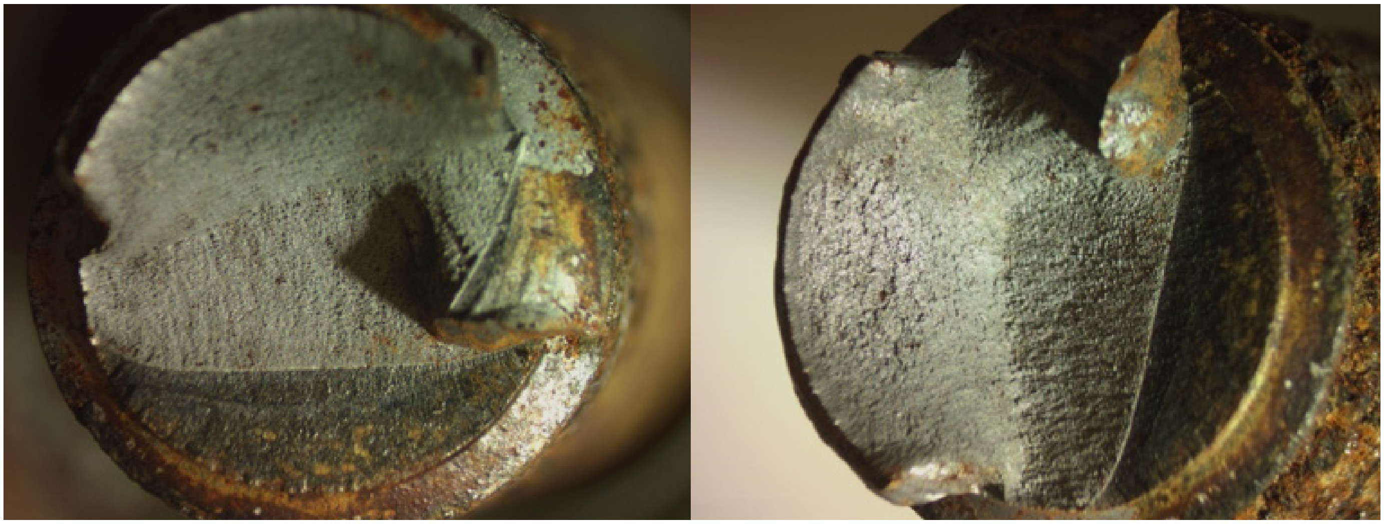


Figure 14
Fracture surface of Bolt #5, displaying a corroded beach marks region, indicative of the exposure of these bolts to a highly corrosive environment after the initial propagation of this fatigue region.

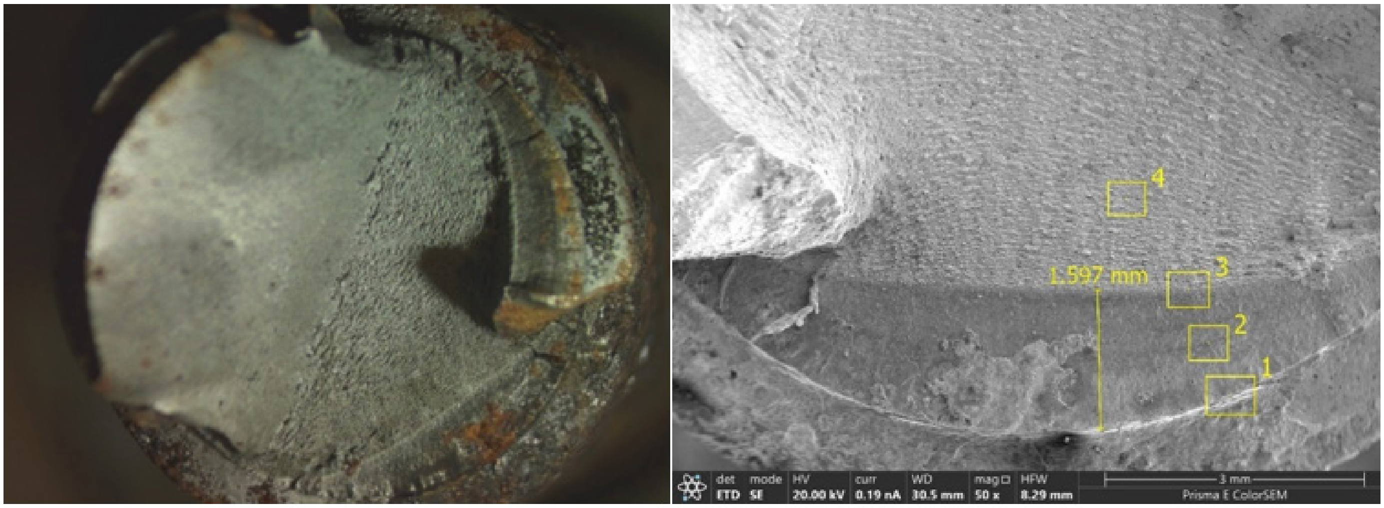


Figure 15
Fracture surface of Bolt #7, displaying a small finely fatigued region covered in corrosion products.

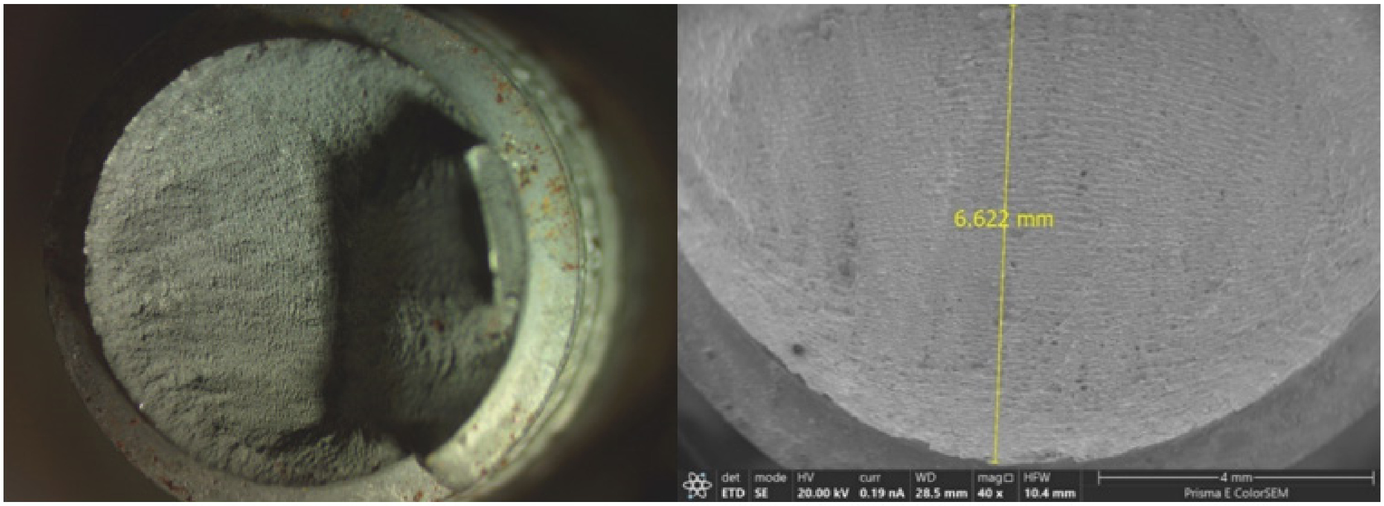


Figure 16
Parallel crack arrest marks observable on Bolt #3, covering more than half of the bolt's surface.

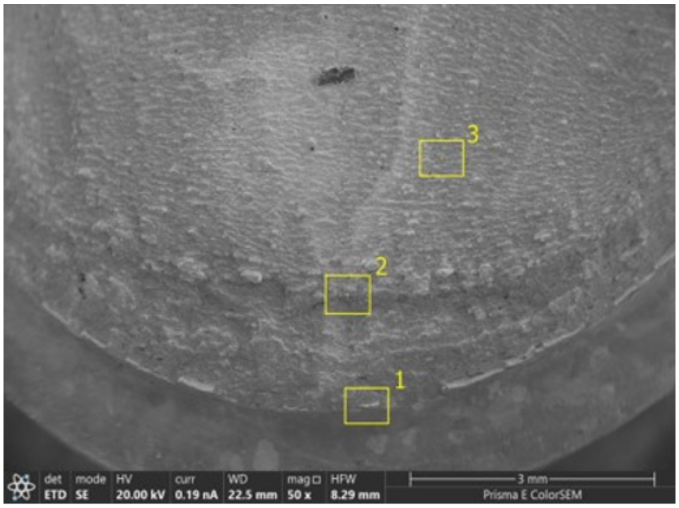


Figure 17
Fracture surface of Bolt #14, showing a region of crack arrest marks.

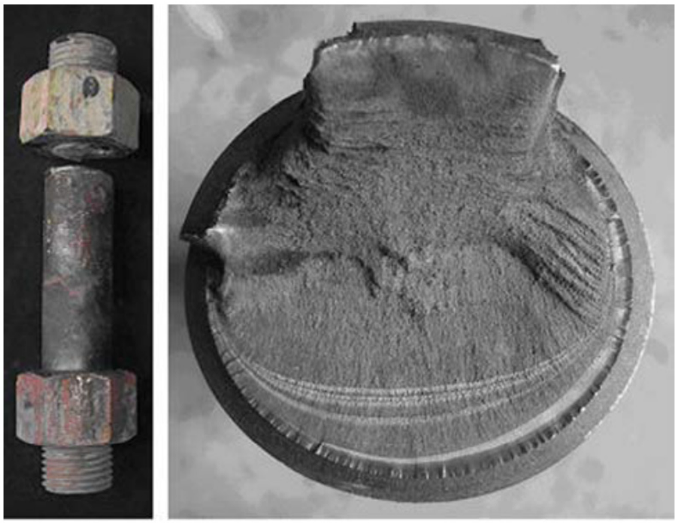


Figure 18
An example of a similar bolt fracture surface as reported in the literature[7].

Based on the operational history of the crane and the fatigue markings noted earlier, it was concluded that failure of the bolts initiated well before the last commission of the crane, but went undetected due to improper maintenance and inspection by the equipment owner (lessor), as will be discussed in later sections.

While it is believed that fatigue failure of the bolts initiated during earlier commissions of the crane, the number of load cycles during early commissions was not sufficient to induce failure. Later commissions of the crane subjected the already partially fatigued bolts to additional cyclical loading as well as operation within a corrosive environment that drove the fatigue cracks further into the bolts' cross section. As the fatigue cracks drove further into the bolts' cross section with each new commission of the crane, the remaining cross section of material experienced high-stress-low-cycle fatigue as evidenced by the pronounced crack arrest marks (**Figures 11** through **17**). By the time the pipeline maintenance company acquired the crane, the bolts were significantly fatigued and close to failure.

To summarize, the bolts at issue were suffering from metal fatigue and stress corrosion cracking before the crane was rented by the maintenance company. The cyclic stresses the bolts had previously been subjected to propagated cracks throughout the material and greatly decreased the nominal level of stress the material could take. The corrosion present on the bolts further exacerbated the decrease in their fracture toughness.

Given the fact that the maintenance company did not expose the crane to loads in excess of the weight of the heating ring, which weighed 500 pounds at most, the possibility of an overload failure can be ruled out. The fact that fatigue fracture occurred at such a low level of loading indicates that fatigue had progressed over an extended period of time to a critical level, and the failure was inevitable, given the history of the crane.

Inspection and Maintenance

The crane's owner's manual requires that, as part of daily maintenance, the crane be inspected for "evidence of broken structural components such as welds and loose fasteners." The manual also states that quarterly inspections are to be done to identify loose bolts on the crane body and the pedestal. In addition, the lubrication and maintenance schedule calls for the owner and operator to check and tighten the pedestal bolts as well as all other bolts on the crane on a weekly basis.

The lessor's inspection logs showed that they failed to perform nearly all the inspections required by the owner's manual. If these inspections were performed, they were not documented. The lessor insisted that, though they did not have a daily, weekly, monthly, or quarterly maintenance schedule as the owner's manual required, there was no need for them to do so — as this requirement only applies to the operators. However, the owner's manual does not contain any section limiting maintenance to the operator. Furthermore, OSHA Regulation 1910.180 "Materials Handling and Storage: Crawler Locomotive and Truck Cranes" requires frequent and periodic inspections to be performed and does not limit inspection to only be performed by one entity in the supply chain[9]. OSHA 1910.180

contains requirements for performing enhanced inspections on cranes left idle for periods between one and six months — and even more extensive inspection for cranes left idle for periods more than six months[9].

The lessor testified that the few inspections they did perform were purely visual inspections and claimed that this was sufficient — and in accordance with the requirements of the manual. While the owner's manual does not state the method by which one should conduct the inspections, this does not limit bolt inspection to being purely visual. Visual inspection of the head of a bolt does not reveal anything about the condition of the bolt below its head.

The inspector should have pulled out the bolts and inspected the interior surface and threads to determine the state of the bolts on at least a quarterly basis. Even if the inspector was justified with visually inspecting only the exterior head of the bolts, the loss of the bolt head's chromium coating should have alerted the inspector that the bolts had been subjected to a degrading environment that was likely to be worse in confined areas such as the bolt holes. Even if the lessor's sole reliance on visual inspection was sufficient, the lessor only performed this inspection immediately after repairs (and before it handed the equipment over to renters), which were documented by the lessor to have been performed on 7/26/2017, 3/3/2018, 11/21/2018, 7/15/2019, 8/15/2019, and 9/20/2019. This frequency of inspection falls well below the requirements stated in the owner's manual.

In addition, the manner in which these inspections were conducted was found to be insufficient. According to their own testimony, the lessor neglected to check for signs of overload after their cranes were returned, ignoring the potential for misuse by previous renters. The lessor knew, or should have known, that their equipment could be subjected to misuse and/or overuse with the potential to exceed its design limits, even if no signs of gross misuse were present on the crane boom.

If they had taken preventive measures to inspect and repair areas of the crane that would likely be harmed by such misuse, they would have identified the progressive fatigue cracking in the bolts and promptly replaced them. The lessor did not lubricate the rotation bolts on the crane. The lubrication acts not only to keep parts running smoothly, but also to provide an additional protective layer against corrosion. Had the lessor lubricated the bolts, they would have likely not corroded as much — and would have likely been able to withstand the operating loads on the day of the incident.

According to testimony, when the bolts were first tightened, they were marked with a painted line. If this line falls out of alignment or the paint cracks, then it is a sign to the inspector that the bolt is no longer fully tightened and must be torqued. The bolts had not been torqued or checked to see if they needed to be re-torqued for the five years the lessor had the crane. The service manager for the lessor stated that it would have been reasonable for them to perform quarterly torque testing of the pedestal bolts.

The lessor's inspection protocol for rotational bolts is to perform torque tests on them, but this was never performed on the bolts. The lessor admitted that they never inspected the bolts for failure, corrosion, or degradation because they believed they only needed to verify the paint on the bolts was not broken or out of alignment. The inspector for the lessor who had inspected the cranes after each rental period was not licensed or certified. This is in clear violation of the requirement in the owner's manual that "only authorized and trained service personnel are to perform maintenance on the crane."

The lessor's documentation shows that their inspections failed to consider the bolts as something that needed to be checked. The maintenance company's crane boom operator performed daily inspections in accordance with the owner's manual. They claimed to have checked for leaks, looked over decals, made sure safety covers and guards were in place, switches functioning, controls in working condition, temperature/oil pressure, hydraulic system, leaks, machine performance, fire extinguisher charged, seat belt, brakes, transmission, tires, etc. These inspections revealed no damage or bends in the crane boom.

The maintenance company was not reasonably expected, nor in the best position, to properly inspect for rusting or cracking of the support bolts. It would be unreasonable for the lessor to expect the maintenance company to perform the necessary inspection given the short period of time the maintenance company was in possession of the crane and the light-load environment they were using the crane for. Therefore, as the next entity in the supply chain, it was the lessor's duty to regularly inspect the bolts and to replace them when necessary.

It was reasonable for the maintenance company to expect that the crane was free of any latent defects. Furthermore, it was reasonable for the maintenance company to rely on the lessor for regular inspections and timely maintenance of any components in need of repair or replacement. Based on provided testimony, the lessor stated that it would be reasonable for the maintenance company to depend upon the inspection performed by the lessor. The lessor additionally stated that they would not hold the maintenance company negligent for not inspecting the bolts. The lessor knew (or should have known) that equipment would wear down if it was not properly maintained and that maintaining their equipment was an important aspect of their business.

The lessor testified that, given the condition of the bolts, they posed an unsafe condition to the user. Despite claiming that the owner's manual did not specify any inspection procedures for them to follow — and repeatedly stating that they followed the manual — the fact remains that the lessor did not perform the inspections required of them in the indicated time spans. Had the lessor performed these routine inspections and any preventive maintenance required by the manual, the failure of the bolts would have likely been prevented.

Though the owner's manual required inspections on the pedestal bolts, it failed to specify what exactly the inspection should entail and what these inspections should identify as deficiencies or hazards. The manual should have mentioned that the bolts could rust or fatigue and the detrimental effects this can have. The owner's manual should have also required owners and operators to remove/inspect the pedestal bolts on a quarterly basis. If such a requirement were clearly stated, the reasons behind bolt inspections would have been made apparent to the operator. This position is justified because a manufacturer/designer of industrial equipment is in the best position to know the weaknesses and hazards associated with their equipment, thereby creating a duty to inform the users of its equipment of known hazards and the most effective means for identifying and guarding against such hazards.

Furthermore, the lessor claimed that if the crane manufacturer had given clear instructions on how to perform the bolt inspections and the danger rust and fatigue posted, they would have followed these instructions. As such, it can be argued that the crane manufacturer holds partial liability in the incident for contributing to the lessor's negligence.

Hydrogen Embrittlement and Inappropriate Bolt Material

The Grade 8 bolts provided by the crane manufacturer were yellow zinc-plated as per ASTM F1941. As previously mentioned, this coating was applied via a process known as electroplating. However, it has been well documented that acid attack from the electroplating process can produce pitting in the bolt as well as inducing hydrogen embrittlement (HE), a complex phenomenon in which atomic hydrogen is absorbed into the metal, reducing the material's strength, toughness, and ductility. HE is known to occur due to a variety of different mechanisms, such as hydride formation, hydrogen-enhanced decohesion mechanism (HEDE), hydrogen-enhanced local plasticity (HELP), and adsorption-induced dislocation emission (AIDE)[10]. While these mechanisms differ dramatically from each other, ultimately, they all manifest cracking in steels through either strain-controlled plastic flow or stress-controlled decohesion.

The strain-controlled mechanism combined with concentrated plastic flow typically results in trans-granular cracking while stress-controlled decohesion results in intergranular cracking[11]. An increase of hardness allows for higher stresses to be sustained by the steel and for more hydrogen to collect at these regions of elevated stress, thereby increasing decohesion-based HE[12].

According to the literature as well as manufacturing standards such as DIN EN ISO 4042, it is well known in the industry that hardness values above 32 HRC will make the material more susceptible to HE[13,14]. While hardness values approaching 40 HRC are considered highly susceptible to HE, materials with hardness values between 32 and 40 HRC can still have considerable susceptibility to HE. A report by one bolt manufacturer states that bolts with hardness values above 35 HRC have the potential to experience hydrogen embrittlement, though failure in bolts with hardness values below this are still known to occur. They also note that this is particularly prevalent in cases where the bolt is acting as a cathode in a galvanic couple or is operating in a caustic or sour environment, as was the case with the subject crane boom[15].

As the subject bolts were found to have hardness values of 39 HRC and were electroplated, hydrogen embrittlement was investigated as a potential factor contributing to the fatigue failure at issue. SEM of the failed bolts identified signs of stair-step cracking and intergranular fracture characteristics with pitting of exposed grains, a telltale sign of hydrogen embrittlement and stress corrosion cracking (**Figures 19** and **20**).

In addition to the stated susceptibility of electroplated bolts to premature failure, the crane manufacturer had

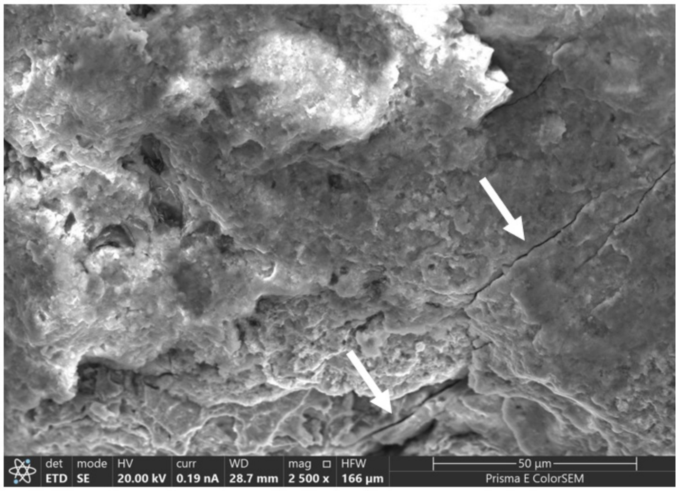


Figure 19
An SEM image of Bolt 10, showing fracture occurring along the grains of the material as well as the presence of stair step cracking along the grains of the material (white arrows).

previously experienced two different crane failures of a similar nature to the subject incident. Around the beginning of 2015, one of the crane manufacturer's cranes fell off the base of the truck body after around three years of operation. The conducted failure analysis investigation revealed corrosion of all the failed bolts as well as corrosion pitting on the threads adjacent to the fracture surfaces. In addition, it was found that the bolts had 39 HRC, above the minimum value where HE and hydrogen induced cracking is noted to be an issue. The investigation concluded that the fatigue fracture was potentially initiated due to corrosion pitting and HE.

Another one of the cranes produced by the crane manufacturer was noted to have experienced failure in March of 2018, around a year after it was first assembled. As was the case with the previously mentioned incident, all of the 14 bolts on this crane were the same Grade 8 steel fasteners utilized in the subject crane. SEM analysis revealed extensive intergranular and quasi-cleavage fracture morphology typical in bolts subjected to hydrogen embrittlement (**Figure 21**).

The failure analysis team concluded that hydrogen embrittlement was likely to have occurred during the manufacturing of these bolts and that the in-service corrosion of the bolt coating while in service provided another source of hydrogen exposure, allowing for additional embrittlement to occur. The team recommended that the manufacturer change the bolts that were utilized on these cranes, utilize lubricant, and inspect the bolts regularly/replace them if they showed signs of corrosion.

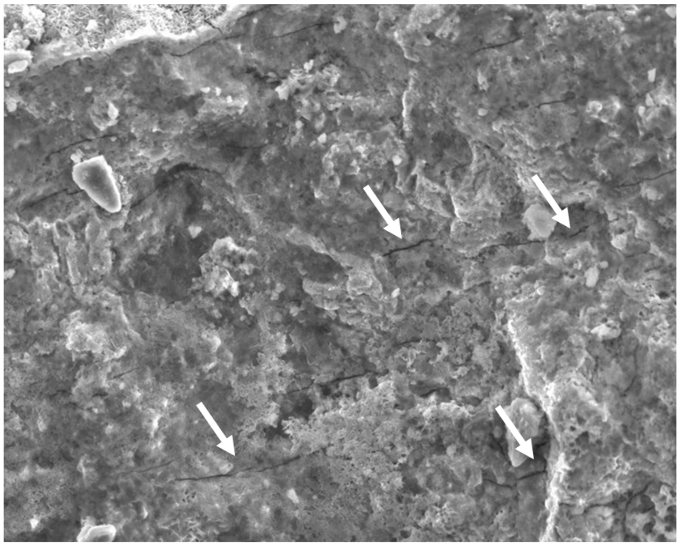


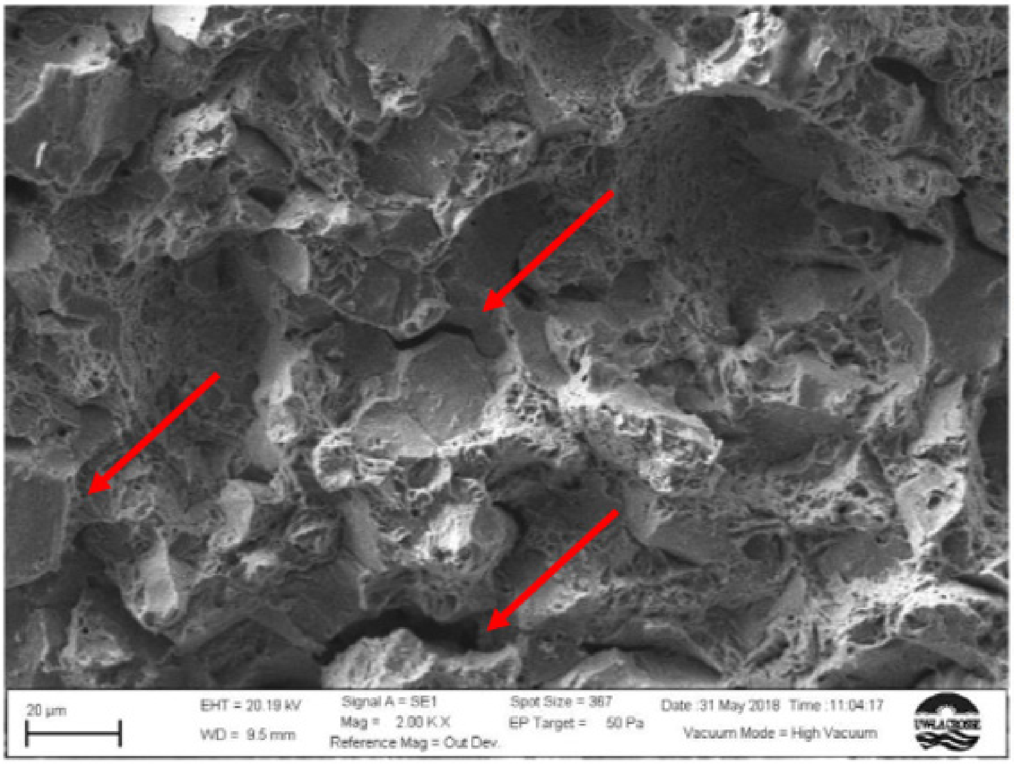
Figure 20
An SEM image of Bolt 5, displaying quasi-cleavage indicative of mixed inter and transgranular fracture.

All incidents happened at least a year after the cranes were put into service. All cases showed corrosion on the fasteners, indicating the coating was insufficient to prevent hydrogen from impregnating the fasteners.

After the 2018 incident, the crane manufacturer contacted the bolt manufacturer and discussed switching the bolts used for the crane. Afterward, a technical bulletin was issued by the crane manufacturer, calling for the stock Grade 8 fasteners to be replaced with zinc/aluminum flake coated Grade 8 fasteners and providing a detailed guide on how to perform this replacement. The zinc/aluminum flake coating on these bolts provided a large decrease in the risk of HE and is shown to provide far greater corrosion resistance than yellow zinc.

This technical bulletin was issued to everyone who purchased the crane attached to its recommended truck body. However, this bulletin was not sent to those who purchased the crane individually, as was the case for the lessor in the subject incident. Had the crane manufacturer sent out this notice to all parties, including the lessor, it is likely that the lessor would have replaced the bolts, and the incident at issue would not have occurred.

According to a report by the bolt manufacturer, the susceptibility of the Grade 8 fasteners utilized in the crane at the time of the incident was well known. This report came out the same year the crane manufacturer began purchasing bolts from the bolt manufacturer. In addition, a report by the crane manufacturer acknowledged the fact



Location 2

This images shows:

- Intergranular fracture
- Secondary cracking
- Ductile tearing on grain facets
- Microvoid coalescence

Figure 21
Intergranular fracture features on the failed bolts from the 2018 incident, indicating embrittlement took place.

that these bolts were subjected to HE from manufacturing.

Since these zinc/aluminum flake bolts have been available since 2011, the crane manufacturer knew, or should have known, about their existence — and the fact that these bolts were more practical for use in their crane. Given these previous failures, as well as documents owned by the crane manufacturer, the susceptibility of their chosen bolts to HE was well known prior to the sale of the subject crane, yet they failed to provide proper bolts for consumers.

Another contributing factor to the use of inadequate bolts was the failure of the bolt manufacturer to inform potential users regarding inappropriate applications that can make the bolts susceptible to this type of failure. Had this occurred, the crane manufacturer would have been more likely to consider purchasing bolts that would have been able to properly withstand their expected environment.

Summary

Evaluation of the failed bolts revealed extensive corrosion and the de-alloying of the zinc chromium exterior surface coatings while the fracture surfaces of the bolts showed comparatively little iron corrosion. This implies that the bolts had been subjected to a harsh corrosive environment for an extended period of time prior to the incident, possibly the lessor's outdoor yard or the heavy industrial environments where previous renters utilized the crane.

Microscopic imaging and analysis of the bolts' fracture surfaces revealed classical characteristics of progressive and partial fracturing of a significant portion of the bolts' cross section over an extended period of time (fatigue failure), prior to the final fast fracture of the bolts' remaining cross section when under relatively low-level load on the day of incident.

Given the short period of time that the crane was in use by the maintenance company, the pre-existing partial fatigue fracture of its bolts initiated prior to the maintenance company's use and continued over an extended period of time while the crane boom was subjected to cyclical loading throughout its lifetime rental history. The bolts were found in a state of severe corrosion that occurred over an extended period of time and prior to their final fracture on the day of incident. The observed corrosion of the bolts resulted in progressive degradation of the bolt material's inherent strength that made them susceptible to fatigue failure over time.

The lessor failed to perform the maintenance outlined in the owner's manual, despite knowing the bolts were potentially exposed to high load-levels as well as highly corrosive environments. The failure to perform routine inspection and maintenance of the support bolts created a latent hazard that was not discoverable by the user of crane (maintenance company). There is no evidence that the maintenance company's activities contributed to the failure at issue. Additionally, since fatigue failure and corrosion of the bolts occurred along the bolts' shaft and below the visible bolt heads, the maintenance company was not in a position to have discovered the deteriorating condition of the bolts, which led to their eventual failure on the day of incident.

Although the owner's manual required inspections on the pedestal bolts, it failed to specify what exactly the inspections should entail and what such inspections should identify as deficiencies or hazards, such as corrosion or fatigue cracks. The owner's manual should have also required owners and operators to remove and inspect the pedestal bolts on a quarterly basis. This requirement is reasonably justified as a manufacturer is in the best position to know about proper frequency of needed inspections and what such inspections should entail. As testified by the lessor's employees, had the owner's manual provided clear instructions for performing routine inspections, maintenance, and replacement of the bolts, when necessary, they would have followed such instructions.

Conclusion

This case highlights the duty of manufacturers to properly consider the function and suitability of the components they source for their products as well as the need for manufacturers to inform consumers regarding the suitability of their products and warn against use in environments known to cause premature failure. It also provides an example of fatigue failure at low levels of applied loading, displaying classical fatigue failure markings. Such an example can be utilized for future failure analysis investigations or educational purposes.

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