Crane Structural Maintenance

Liftech has learned a great deal about crane structural maintenance from five decades of assisting clients with fatigue and fracture issues. Michael Jordan and Simo Hoite, Liftech Consultants Inc., offer some observations and recommendations based on the company's vast experience.

All cyclically loaded cranes develop cracks over time. The cracks grow during normal operations. The cracks usually grow slowly at first and then rapidly as they approach a critical size. If a crack reaches a critical size, the component fails without warning. This is a serious threat, but it can be managed by following a structural maintenance programme executed by competent personnel.

The goal of crane design and structural maintenance is to limit the risk of catastrophic collapse to an acceptable level. Reduce the risk, but not eliminate the risk. When a designer asks a client, or other stakeholder, who has not considered the issue before, "What chance of collapse is acceptable?" The answer is almost invariably, "No collapse is acceptable."

Unfortunately, there is always a chance of failure. The reliability is never 100%. Less than 100% may seem unacceptable to the layman but it is unavoidable. The failures are called "fatigue" failures, but the atomic structure of steel does not get tired. Instead, stress fluctuations cause some of the atomic bonds to fail (see Figure 1).

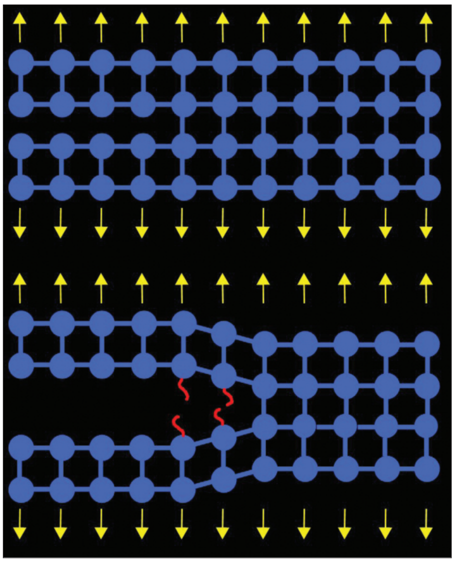


Figure 1: Atomic bond failure = crack growth

The separation causes a crack, however small, to grow from an initial discontinuity. This separation releases energy. The structure deforms a little with each cycle, and the crack grows incrementally until the atomic bonds in the steel can no longer absorb the energy generated by the deformation. The crack then shoots across the steel at the speed of sound - bang - sudden failure. This is steel fatigue failure.

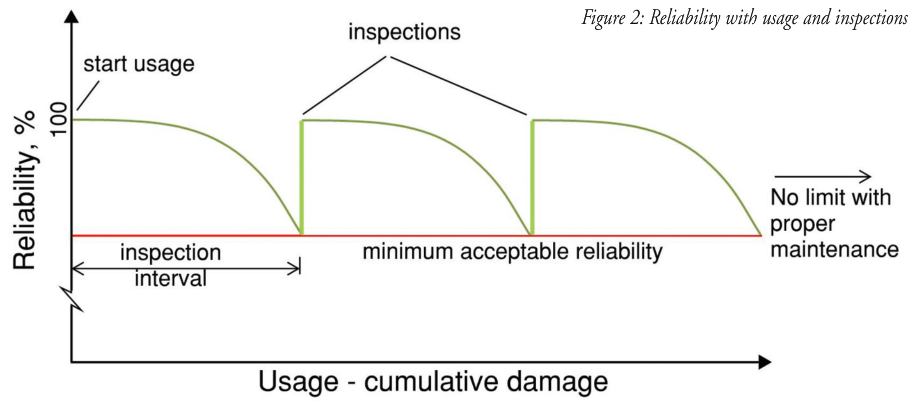
Clients often ask us to verify that the crane design life will be met or to calculate the remaining fatigue life of an older crane. This cannot be answered without further explanation. The "life" of a structure is not a life in our normal sense of the word. The fatigue design life is how many loading cycles are needed to cause the laboratory test sample to fracture suddenly. The term is often misunderstood. It is not how long a crane can be used before it must be replaced, and it does not mean the crane does not require inspection during its service.

How can the reliability be improved from 97.7% to 99.999%? This increase is achieved by structural maintenance that includes a detailed inspection plan based on fracture mechanics and statistical analysis.

For over a century, fatigue failure without advance warning was not recognised as a significant threat to the integrity of cranes. Fatigue fracture as a phenomenon was not studied widely for crane structures until the 1960s, and fatigue design and inspection was not applied systematically to cranes until the 1970s.

Liftech has investigated many fatigue failures. The underlying causes in nearly every case of fatigue failure are one or more of the following: poor design, poor materials, poor workmanship (see Figure 3), incompetent or inadequate inspection during construction, and improper structural maintenance during service.

Figure 2: Reliability with usage and inspections



Reliable life is a better term than design life. Liftech defines reliable life as the number of applied cycles needed for the reliability to fall below an acceptable level (see Figure 2). The reliable life may be extended by periodic inspection and repair.

Fatigue design standards provide guidance for calculating reliabilities based on the applied cumulative fatigue damage and the structural detail. Fatigue damage is the calculated sum of the stress ranges cubed times the number of cycles. Liftech usually recommends a structural reliability of 99.999% for fracture critical components and 99.9% for non-fracture critical components. Allowable stress ranges specified in typical codes are based on a 97.7% reliability.

Figure 3: Roughly cut stress relief hole

Complying with codes is often not enough to produce a reliable crane. Some poor details comply with the codes (see Figure 4). Liftech does not accept some details regardless of the code standards.

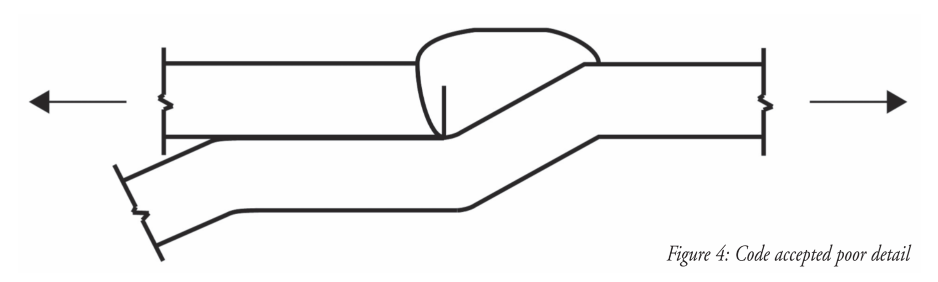


Figure 4: Code accepted poor detail

Figure 5: Low profile crane - late 1960s (subsequently raised)

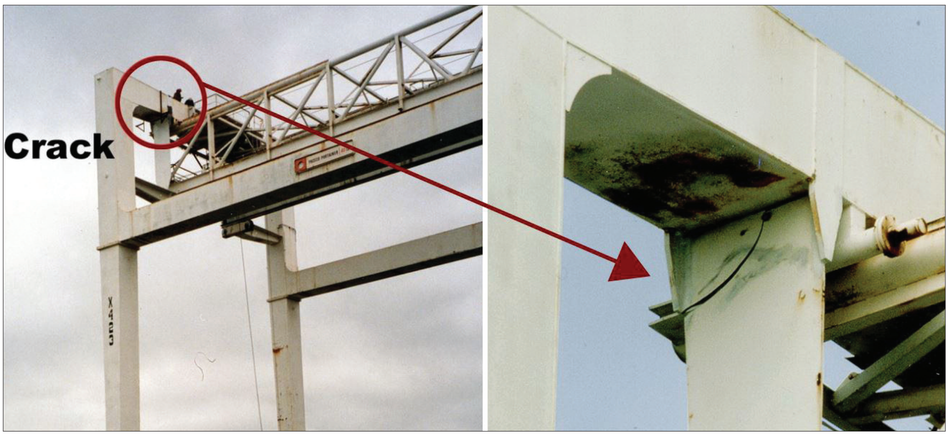


Figure 6: Fractured hanger plate

Two different fatigue failures on low profile cranes designed by Liftech

The structures of the two low profile cranes in the following discussion were similar. In both cases, the boom hanger supports failed because a small crack at the outer edges of the hanger plates was not found or recognised as a threat. Fortunately, the hanger design was conservative. There are a total of four 600mm wide boom support hangers, two at the landside and two at the waterside. If one of them failed, the remaining hangers were designed to carry the load and the boom would withstand the extreme torsional stresses.

One crane was built in the late 1960s. The other was built in the 1970s. See Figure 5 for an overall view of the 1960s crane. The image is from many years after the crack was discovered and repaired, and after the crane was subsequently modified to increase the lift height.

Low profile crane circa late 1960s

One hanger failed on a 1960s crane. An undiscovered fatigue crack in the boom hanger plate had been growing for over ten years. When the crack reached the critical size, the slow growing crack suddenly shot across the plate jeopardising the boom support (see Figure 6). The boom dropped a little and twisted but did not fall. Under the Liftech engineer's supervision, the boom was retracted while being supported by only one of the two waterside hangers.

The crack that caused the failure was not detected, even though an inspection of critical points was performed every few years. When the engineer looked at the failure surface a few hours after the accident, he got wet paint on his hand. He learned the hanger had been recently painted because it had been MT examined the day of the failure. The paint had been removed so the MT examination would detect cracks, if any. The critical cracks were not found, and the test area was repainted.

The inspector did not know to look at the edge of the plate, which was the most probable location where cracks would initiate. The inspector and the engineer observer, although conscientious, did not know what they were looking for or what the arrow pointing to the plate edge, in the inspection manual, meant. They only looked for cracks about three inches from the edge. The owner was paying for a worthless inspection.

Low profile crane circa 1970

Two waterside hangers failed on a 1970s crane. The 115m long boom freefell onto the vessel being unloaded. A bit of good luck saved the operator from serious injury - the operator's cab landed on a container loaded with soft cheese. The cause of the failure was similar to that for the 1960s crane. The cranes did not have a well-thought-out structural inspection plan.

When inspectors discovered 3mm cracks on the edges of the hanger plate, the crane maintenance crew did what they thought was a cure and ran a weld bead over the crack, so the crack was no longer visible. This did nothing to repair the damage to the crane and the crack continued to grow, until failure.

In addition to the improper maintenance, it turned out that during crane fabrication, the steel specified on the crane design drawings was not available, so the purchasing agent bought what was available. The steel purchased cost more than the steel specified, so it was assumed to be better.

The steel was very brittle firebox steel. The steel fracture toughness was much less than specified, so when one hanger collapsed, the other hanger, that also had a small crack, failed due to the impact load. If the material met the specification, neither would have failed.

These examples are not as uncommon as one might expect.

Lessons learned

Liftech has learned a great deal about crane structural maintenance from five decades of assisting clients with fatigue and fracture issues. The two examples illustrate what can happen. Following are some observations and recommendations based on our experience. In the design of a crane, never unconsciously deviate from a standard. But at the same time, use common sense when following code requirements.

The codes are guides and they should be followed, except when an experienced and a qualified engineer determines there is a good reason for deviation, such as for requiring a detail better than the minimum specified. The guidance provided by the standards is necessary but limited. Some issues are not addressed. For example, good fatigue details may be severely downgraded by attachments not shown on the drawings, such as electrical, walkway, elevator supports, holes for conduit, reinforcement around holes, or shipping braces.

Limitations of finite element analysis: FEA results are not directly suitable for determining stress ranges at local details such as at the toe of welds. Special adjustments are needed to determine meaningful local stress ranges.

However, FEA can be used to determine the relative improvement between the original detail and a proposed improved detail. This method was used to design the improvements of a forestay-to-boom connection plate. The improvement was trimming the boss plates to allow the connection plate to flex, thereby reducing the stress as the boom girder rotates in torsion due to trolley loading (see Figures 7a - 7c).

Figure 7a: Forestay boom connection plate failure

Certain structural details are so problematic from a fatigue and cracking perspective that Liftech developed some acceptable and unacceptable structural details. The details are included in our crane specifications, in some texts, and are on our website. Avoid locating stress raisers near each other. If the stress raisers are unavoidable, combine the stress concentration factors when calculating the stress. It is worthwhile to calculate cumulative damage and determine where to focus structural inspections. Often only a relatively few members need frequent inspection, while the rest could be inspected less frequently. This can save significant inspection effort and costs (see Figure 8).

The fabrication shop should follow the design approved by the engineer. The shop may make a cut or add a plate to solve a problem, but may inadvertently greatly reduce the reliability and reliable life of a critical detail or component. The responsible structural engineer should be aware of pertinent fabrication processes. If the shop does not welcome the engineer, there is a problem. The engineer should look at the work and ask the fabricator for suggested improvements that will make fabrication easier. The fabrication inspection team must include qualified and knowledgeable engineers. The goal of inspection is not just to create a document. The primary goal is to look for and identify problems, so they can be corrected. Of course, reports should document the findings, but if time is limited, get the fabricated product right. Document the limitations.

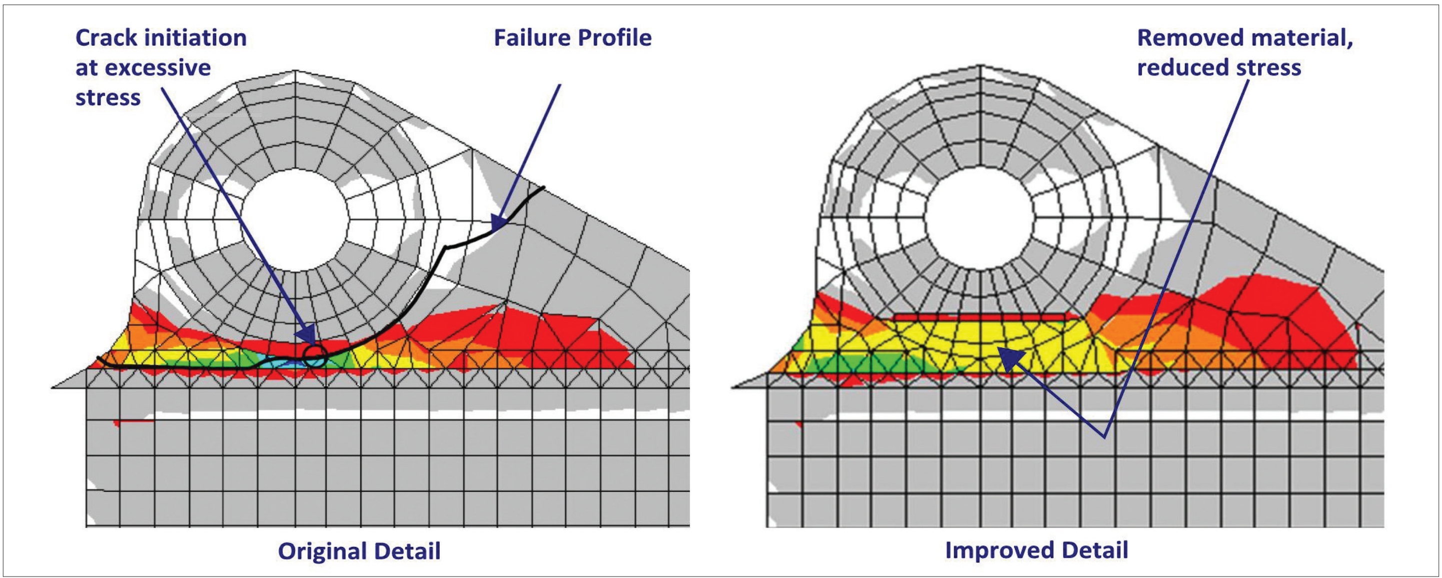


Figure 7b: FEA of original and improved details

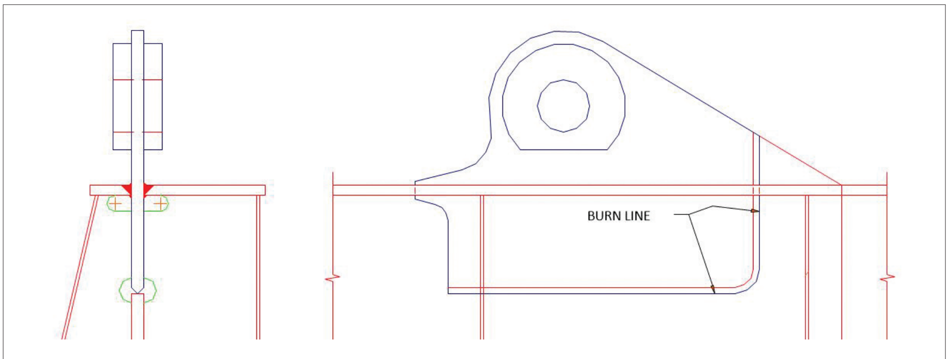


Figure 7c: Drawing showing improvement by removing material

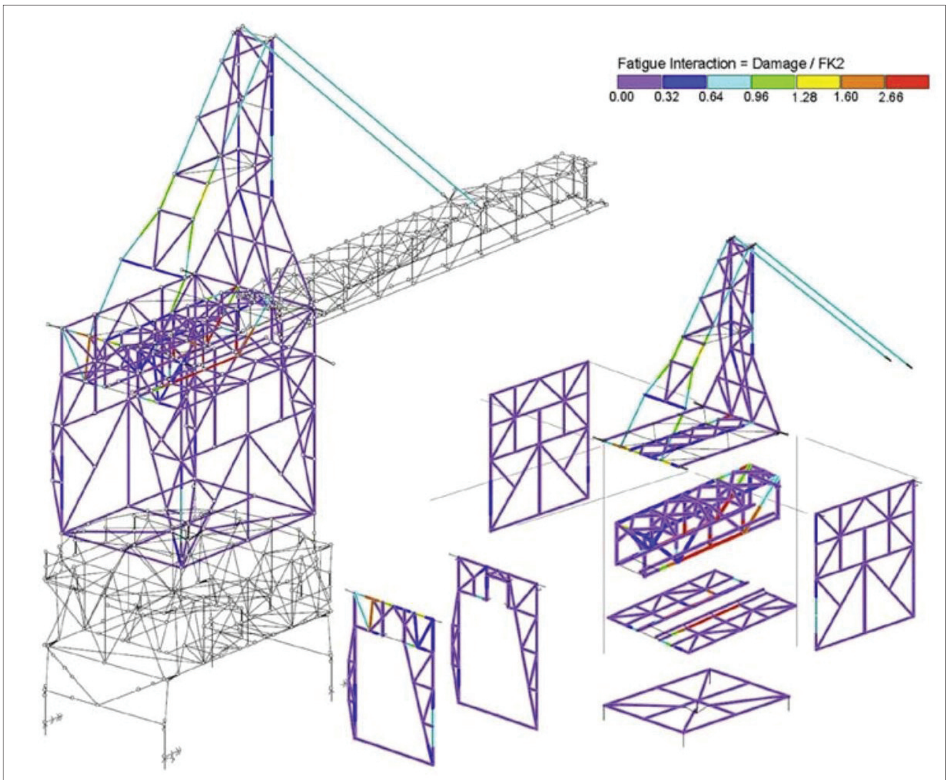


Figure 8: Calculated fatigue damage interactions – portions of a structure

Crane structures need a formal structural maintenance manual

After the 1970 crane failure occurred, SeaLand, the owner, recognised there was an ingredient missing. A specification prepared by consultants and SeaLand engineers was issued to the bidders. The specifications were detailed and included the usual structural provisions, but no structural maintenance provisions. SeaLand realised this missing ingredient and set about preparing a suitable structural maintenance manual. A comprehensive manual was prepared by the original specification team.

The structural maintenance manual provisions were used by SeaLand to improve the reliability of existing cranes and new cranes. The results have been remarkable. Although most of the old SeaLand cranes are now obsolete and retired, some are nearly sixty years old and still reliable and productive. Today, many manufacturers and crane designers provide structural maintenance manuals that evolved from the original SeaLand manual.

Future structural maintenance

Methods of detecting structural problems will continue to improve. For instance, UT NDT has been improved with phased array testing. Drones will play a greater role. We expect strain gage readings of member stresses will be implemented. Remote solar powered equipment will be mounted at strategic points and report data wirelessly. This data will include stress spectrums that will allow more accurate determination of inspection intervals.