STS Cranes – 'Thorough' Structural Examination

Most operators do not implement their structural maintenance practices and often don't inspect in a regular intelligent way. In this article Michael Jordan, CEO at Liftech Consultants explains the current situation…

Three in the morning on a cool, foggy, and windless day, the structural engineer arrives at the ship-to-shore crane. One boom support hanger is fractured. The low profile boom is extended over the ship, which is now unable to depart as planned because the boom is in the way. Why did the hanger fail? It was overload tested just weeks earlier. So how could it not be strong enough? Why didn't both hangers fail like they did on the Port Elizabeth low profile crane? How can we roll the boom back and free the ship? The hanger failed when a fatigue crack grew to a critical size. The size is critical when the work done by the deflecting cracked structure exceeds the work absorbed by the cleaving steel, resulting in brittle fracture. It is a stability problem, like when a rolling cart passes the crest of a hill, and rolls down the other side. This failure could have been avoided if the personnel involved in the "thorough" examination understood the issues. The overload test only deals with the yield strength of the structure. It cannot test the fatigue strength after there is more use. It only tests the present condition. Later, after more load cycles, which make cracks grow, the lifting capacity is less. Cracks grow. Once the "cart" rolls over the crest, even a little: BANG! Oops! The hanger breaks. The "cart" looked so benign sitting on the crest. But once it has rolled over the crest there is no stopping it. Who knew that there might be a problem not revealed by the overload test? The structural engineer knew. The boom did not fall because the structural engineer anticipated the danger and, although not required by any code or specification, he designed the boom support hangers so if one failed the remaining waterside hanger could carry the entire weight of the boom. He spent an insignificant amount on the structural cost, saved the stakeholders a bundle, and probably saved the operator's life - a very big benefit for a very small cost.

Boom or bust

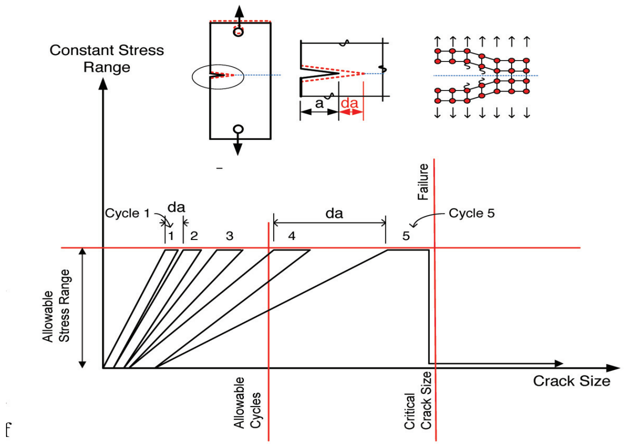
How do we safely move the boom? The boom had rotated so much that the walkways interfered with the hanger. But there was no structural damage to the boom or the remaining hanger. The situation just looked bad. Answer: Cut off the walkways and roll the boom back, riding on only one hanger. When the engineer explained the solution, those standing next to him on the boom were unconvinced. Even though he told them the crane is designed for this event, they all quickly climbed down to the wharf and stood clear to watch what they thought would be a disaster. The walkways were cut loose and the engineer, who was never before allowed to operate the crane because the lawyers wouldn't allow it, retracted the boom and went home to bed. A nuisance but no disaster! But there is one more event worth mentioning. When the engineer climbed to examine the failed plate, he discovered wet paint on the hanger right where the brittle failure occurred. Why was there wet paint? The original paint had been removed and the crane had been inspected by magnetic particle examination and then repainted the day before! So what went wrong? There was a load test and there was an inspection. But the players, although competent and conscientious, simply didn't understand fatigue and brittle fracture. They thought the overload test proved the crane was safe, a common misconception.

Brittle fracture

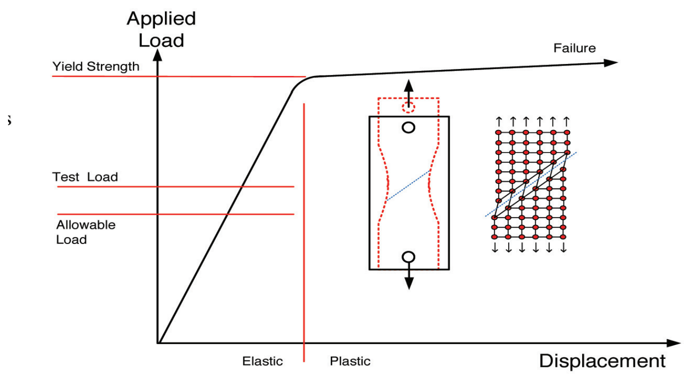
The phenomena of brittle fracture in steel are complex. Fatigue crack growth is also complex. Both brittle fracture and crack growth are understood by many engineers, but not by many maintenance personnel. So let's learn. The Fatigue Criteria sketch explains what happens in simplified terms. As loads are applied, cracks grow and they grow exponentially until the component fails. The sketch shows a simplified, condition of a notched bar subjected to only five load cycles, a fictitious situation but sufficient to explain the principles. The stress pulls the atoms, the dots, apart. They are trying to hold on but eventually the bond between the atoms at the root of the notch break. The crack grows until sudden brittle failure: BANG! Oops! Understanding fatigue damage and failure is very simple except for a myriad of difficulties. If you have ever split a log for kindling and watched a piece fly off, you saw a brittle fracture. A small tap will send the piece on a speedy flight. Where did the kinetic energy come from? Certainly the tap wasn't enough. The energy was stored in the elastically flexed piece and was just waiting for the chance to depart. This is brittle fracture. We hope the following explanations are enlightening.

So what are the difficulties?

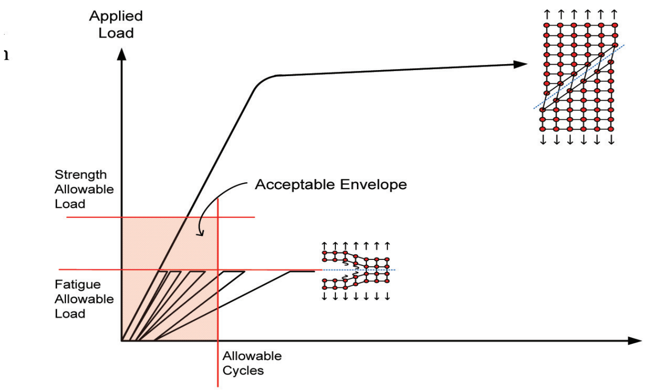
One difficulty is acceptable risk. The allowable fatigue damage is based on thousands of fatigue tests, but only on tests. No mathematician or computer program can accurately predict the performance of a particular detail subjected to a particular experience. The test results are the best we can do now. We have a lot of statistical data but the scatter is large. We must deal with probabilities; our work is not an exact science. One problem is, like snowflakes, no two welds are the same. They may be very similar but they are not the same. So we rely on statistical analysis of test data. A large amount of test data has been generated. Welds are classified according to the details. For each class allowable stresses are determined based on reliability. For fracture critical components, that is, those whose failure would



Fatigue Criteria



Strength Criteria



Combined Strength and Fatigue Criteria

be a catastrophic, the chance of failure is one in fifty for each detail, if the structure is used as assumed and never inspected. These are unacceptable odds. The odds must be improved by "thorough inspections." Since the risk is never zero we must live with some chance of a catastrophe. The crucial question is: What chance of catastrophic failure is acceptable? The code allowables are based on one failure in fifty, if there are no "thorough" inspections. These are unacceptable odds. They must be increased. The most economical way is by intelligent, economic periodic inspection. Many standards require periodic inspections, but do not specify an acceptable risk. Liftech uses a risk of failure of 1 in a 1000 for non-fracture critical components, those whose failure would be a nuisance and one in 100,000 for fracture critical components, those whose failure would cause a catastrophe. These reliabilities can be achieved through the use of fracture mechanics analysis and competent periodic inspection.

Misnomers

The situation is exacerbated by many misnomers. The term "fatigue" implies that the steel gets old and tired like an animal. Steel does not get old and tired. What we call fatigue is simply crack growth. Crack growth starts at an initial discontinuity. All welded structures contain discontinuities, especially at the toe of the welds. When fluctuating cyclical stresses are applied the cracks simply grow. The atomic bonds between atoms break. This transfers more stress to remaining atoms and the more atoms with broken bonds, the faster the crack grows. Once the crack is large enough, the structure fails suddenly without warning, just like the hanger failed. This is shown on the figure - Fatigue Criteria. An example of the how the misleading term, fatigue, causes confusion is evident by the wording in section 6.3 of the Code of practice for the use of cranes Part 2: Inspection, maintenance and thorough examination -Cargo handling cranes of BS 7121-2-9:2013, an excellent guide and a step in the right direction: "Steel structures suffer from fatigue, a process which can create cracks that propagate over time." Fatigue does not create cracks, the cracks, although undetected, are there initially. Fatigue is the growth of cracks. Fatigue does not mean the steel is tired and aging. The British Standard correctly calls attention crack initiation at undetected weld discontinuities. Clearly, undetected weld discontinuities can and do cause serious failure. Another misunderstood term is "fatigue life." The structure does not die or even need to be considered unreliable because its use is longer than the fatigue life. The issue is cumulative damage and the resulting reliability, which depends on the applied load and the number of applications and the fatigue strength of the weld detail. The acceptable cumulative damage can be determined. The reliability can be determined using fracture mechanics and statistical analysis.

Thorough examination

Most cranes come with a recommended inspection regimen and, based on Liftech's research, most operators don't follow these recommendations. They modify to plan without sufficient knowledge to make cost effective decisions. Some details that should be inspected are not and some that aren't worth being inspected are. Considering the cost of inspections, attempts to not perform the full regimen are reasonable. Just as for earthquakes and high winds, the chance of a catastrophe fatigue failure is low and is very unlikely to occur during a particular person's watch. But they do occur, sooner or later. Failure is unlikely. The damage, however, may be great. In effect, there is zero chance of an infinite loss.

Ductile shear failure

To complete the picture we should look at the more easily understood mode of failure: ductile plastic failure. The most common example of ductile plastic failure is the tension bar strength test. The mode is very different from the brittle fatigue failure mode. The atoms resist the applied load through shearing stresses. The atoms slide by each other and before collapse the distortion is great. Imagine a bent mild steel bar. At first it is elastic, the displacement is temporary. When the load is removed the bar returns to its original shape. If the applied load is increased beyond the elastic limit the bar bends plastically. It remains bent even after the load is removed. The failure is stable and slow, no sudden collapse. The yielding bar gives a warning that the bar is failing. The criteria for this mode is simple, strength is the primary variable. If the bar passes the load test, it is ok. It is strong enough and we can depend on its strength. When subjected to loads, the displacement doesn't grow with time.

The acceptable envelope

The third sketch presents the acceptable envelope. The envelope is bounded by both the static strength limit and the fatigue limit. The allowable load and cycle boundaries will vary depending on each situation. Some "thorough examination" recommendations with comments:

- Follow the spirit of the British Standard with the following amplifications and exceptions, when the exceptions are supported by competent engineering analysis.
- Use a 1 in 1,000 chance of nuisance failures and a 1 in 100,000 chance of a catastrophic failure.
- If you have a limited budget, which most have, concentrate on avoiding catastrophes and tolerate nuisance failures. Put your money where it does the most good. Make decisions based on rational engineering analysis.
- Educate inspectors and maintenance personnel about fatigue phenomena so they know what to look for, how to look, and which indications are important and which are not.
- Use visual inspection; but in addition, always use some magnetic particle or similar NDT methods to examine the surfaces at weld toes. Inspect full penetration welds using ultrasonic examination. Visual inspection isn't useless but remember by the time you can see a crack, unaided, the number of load applications before failure is often five percent of those already experienced. So a visible crack means failure will be sooner rather than later.
- Determine inspection intervals based on your acceptable risk. Use an acceptable risk approach and not on approach based on predicted crack growth size studies. Base the interval on crack initiation and the ability to find cracks.
- Determine reliability based on fracture mechanics, and not age, to determine if the structure is safe to use. Some of our cranes that have been well maintained remain reliable for twice the "design life."
- Identify the fracture critical components on the structural drawing and show the ratio of the calculated cumulative damage to the design allow able cumulative damage for each component.
- Keep well documented records of inspections and findings. If you have a large number of cranes, create a database so you will know which details are problematic.

More to come

We and others will have more suggestions and comments. We hope this discussion is the first step in our journey to provide safer and more reliable structures at reasonable costs.