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STRUCTURAL FATIGUE HAPPENS: Maintain Your Cranes!

By Patrick McCarthy

INTRODUCTION

Maintenance is defined as "the work of keeping something in proper condition; upkeep." Most people are familiar with maintaining a car, mechanically—oil changes every 5,000 km or so and other regularly scheduled service at varying frequencies—depending on the car design and usage. Similarly, structural maintenance is most efficiently, i.e. cost effectively, achieved through varying inspection intervals for the different crane components, depending on predicted cumulative "damage." In this sense, cumulative damage refers to fatigue crack growth, not accidental damage.

For a crane structure, maintenance includes frequent visual inspection, periodic non-destructive testing (NDT), and repairing any cracks or damage caused by regular usage or accidents. Regular maintenance is not only essential for a reliable crane but is *recommended* to justify the allowable stresses. See BS 7608, Annex A[1]. The crane is not designed to last forever with no limits on its fatigue life. This is impossible. Cranes will experience fatigue crack growth and if used indefinitely without inspection will eventually fail. The designer and operator must recognize this.

This article discusses the rationale behind structural maintenance programs for quayside container cranes.

THEORY

Unfortunately, even a "perfect" weld is never perfect. All welds contain microscopic discontinuities—cracks. Millions of these tiny cracks exist in all welded steel structures. See Figure 1. Most discontinuities are at first either undetectable by standard non-destructive testing (NDT) methods such as MT, UT, or DPT; or are detectable but acceptably small. Most detectable cracks in relatively new cranes occur at details that are poorly designed, poorly fabricated, or both. We refer to these cracks as infant failures.

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[1] See References.

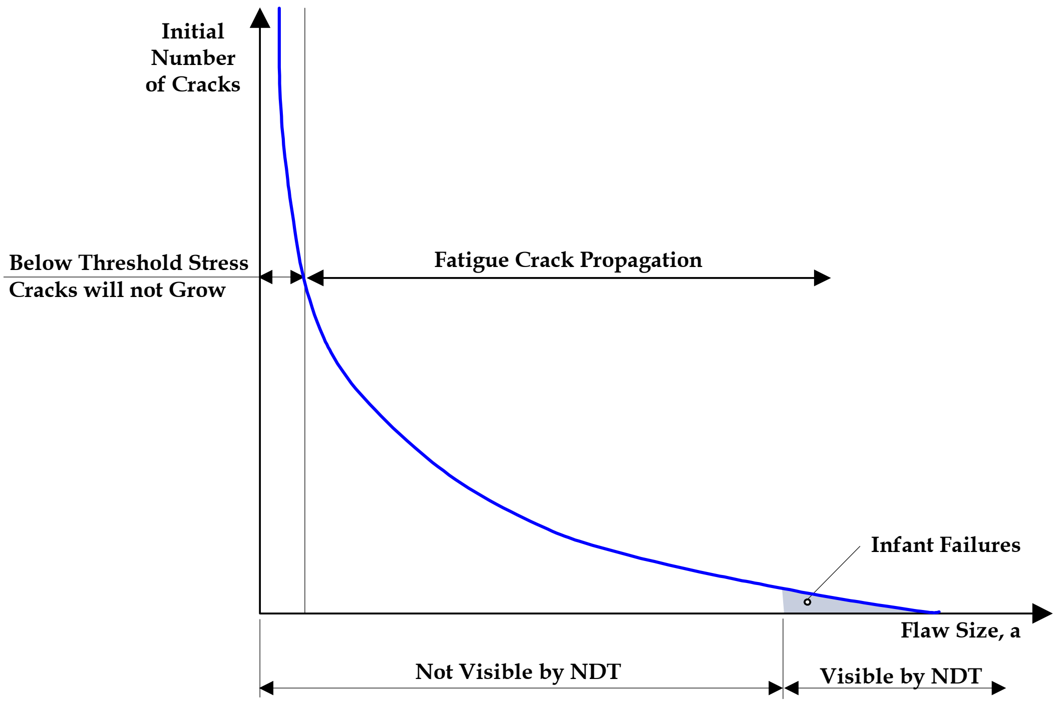

Figure 1: Size and number of cracks, initially

Crack Growth

Below a "threshold stress" range, cracks do not grow. In many critical details, the stresses exceed this level and cracks will grow due to fluctuating stresses. If left unchecked, the cracks will grow until failure. The mode of failure is brittle and sudden, without warning. The fatigue crack growth rate is influenced by the magnitude of fluctuating stresses, crack size, and plate thickness, as well as environmental effects such as corrosion. As shown in Figure 2, a typical fatigue crack's life is primarily spent in Region I, where it is not detectable by NDT. See Rolfe and Barsom. After the crack is detectable by NDT, it will follow a predictable rate of growth through Region II, until the size of the crack is such that the rate of growth increases rapidly in Region III. The number of cycles between inspections, the "inspection interval," should be less than the number of cycles after the crack is detectable and before rapid growth occurs.

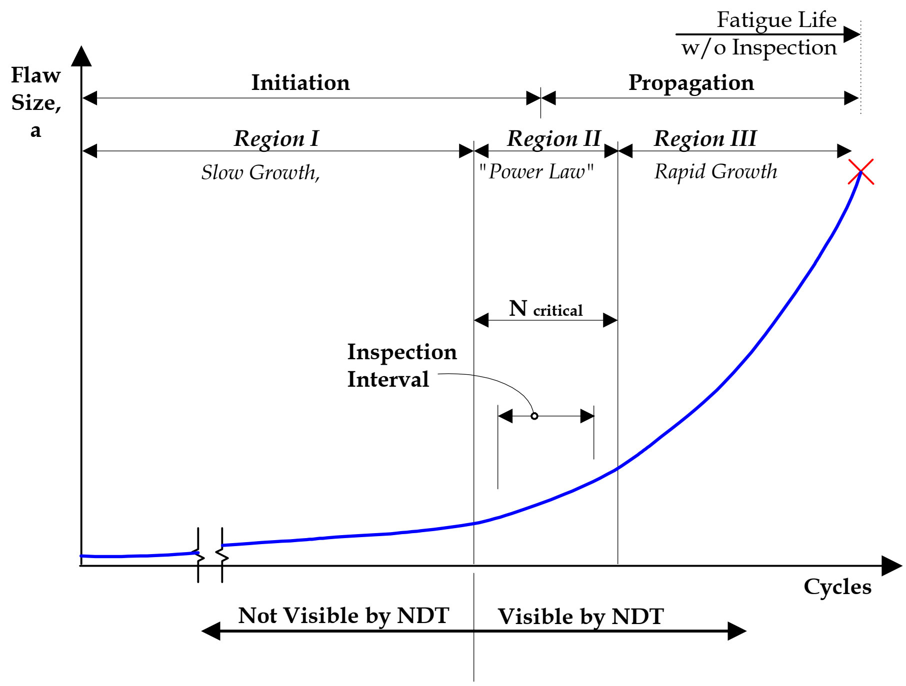

Figure 2: Growth of a single crack

Fatigue Damage

Crane components experience a spectrum of stresses while operating. For instance, the forestay experiences a much greater stress range when the trolley lifts a heavily loaded container at full outreach than when if lifts an empty container half way out. To account for this, a design spectrum of expected lifted loads and trolley travel needs to be determined. The concept of cumulative fatigue damage can then be used by applying Miner's rule:

Fatigue damage = Σ (Stress range^3 x number of cycles) for the entire stress spectrum.

See BS 7608, Annex F or Maddox, Appendix II for cycle counting methods. The calculated cumulative fatigue damage can be compared to the allowable damage, "fatigue strength," for the weld detail.

The fatigue strength of weld details is determined from evaluating thousands of tests. The tests are performed with varying parameters, such as stress range, and the number of cycles to failure is found. See Figure 3. The test data has considerable scatter, so both the mean and standard deviation of the data are reported. This data is used to determine the probability of failure of a given detail subjected to a stress spectrum for a specified number of cycles. The "reliability" is one minus the probability of failure.

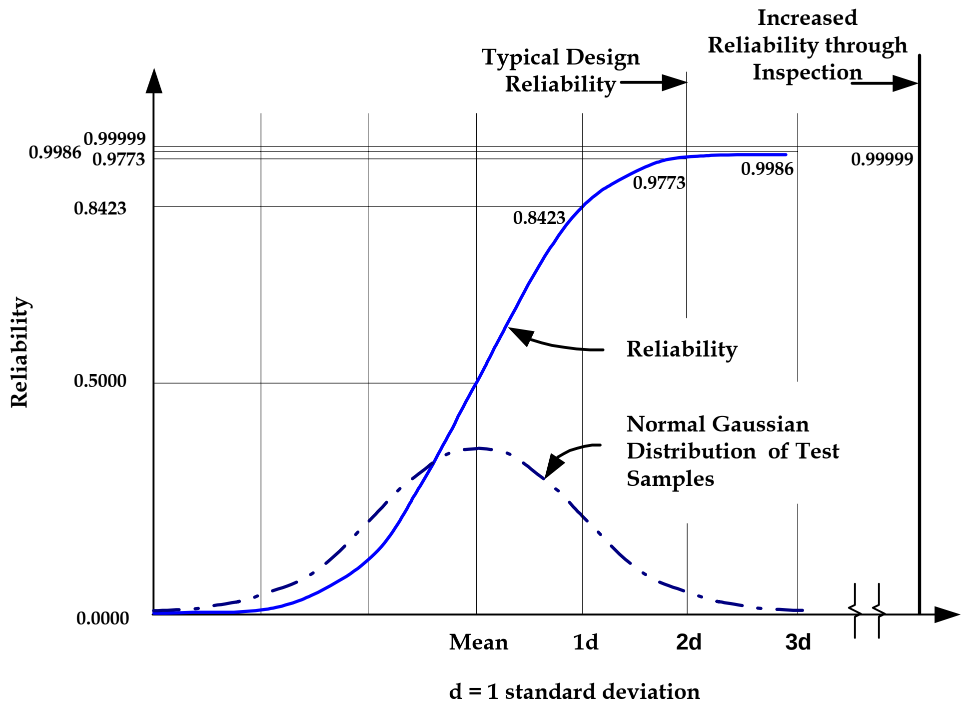

Figure 3: Reliability of a given weld detail

Reliability

Since the data has considerable scatter and as-built conditions are not well known, the results are approximate. If the stress spectrum and number of cycles change, the reliability changes accordingly.

The usually specified reliabilities are 0.8423 and 0.9773, (one and two standard deviations above the mean) for non-fracture critical and fracture critical members, respectively. A fracture critical member (FCM) is a tension member or the tension region of a component whose failure would be expected to result in collapse of the crane or trolley, or dropping the load. These reliabilities by themselves are not very high. If the structure were subjected to the design cumulative damage without inspection and repair and the FCM details were working to the allowable limits, more than one detail in 50 would fail. This would clearly not be acceptable.

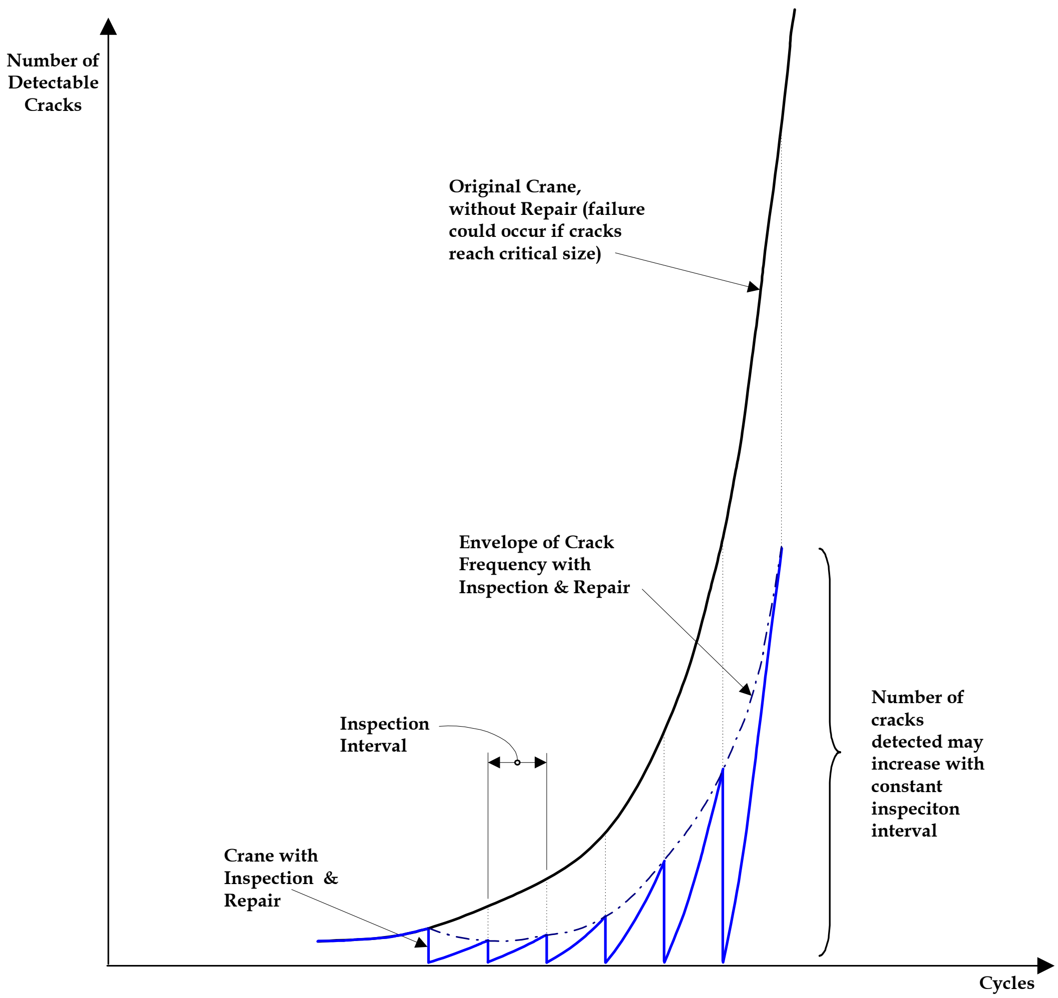

Figure 4: Number of detectable cracks in the crane with and without inspection and subsequent repair

Inspection

To maintain acceptable reliability, the crane needs periodic inspection and repair. The periodic inspection intervals should be long enough to make the inspection economically feasible, but short enough to detect the crack before it reaches an unstable state. Inspection intervals are determined using statistical test data, expected crane usage, calculated cumulative damage, and desired reliability. Those details that are more important and are more likely to fail are inspected more often.

The recommended process is to analyze the crane, calculate the expected fatigue damages for welded connections based on the design spectrum, and select inspection intervals to achieve a desired reliability. Figure 4 shows the schematic relation between the number of detectable cracks versus the number of cycles. As mentioned, at low stresses cracks do not grow at all. If the crack and a small affected region beyond the crack are removed and the weld is repaired, the life of the detail starts over. By inspecting the crane and repairing all detected cracks, the envelope of crack frequency is effectively shifted down. As shown, however, as the crane ages, more cracks may appear for a given inspection interval. This is also as expected from looking at Figure 1. Initially, there are many smaller, undetectable cracks. As the crane ages, these cracks grow. At some stage, possibly well beyond the original design life, the frequency of cracking may be such that it is no longer economically feasible to keep repairing the cracks reliably. If weld details are improved through repair, however, the number of detectable cracks could decrease with time. Either way, with proper structural maintenance a crane will usually first be obsolete due to insufficient size or productivity, or mechanical or electrical reasons. With proper maintenance, a design life reliability of 0.99999 or more can be achieved.

OLD CRANES

For new cranes, owners should be aware of and plan for structural maintenance when issuing technical specifications. For older cranes, owners should review their structural maintenance programs if existent, or develop them if not. Developing a structural maintenance program for an older crane has some advantages over using a program developed during the crane design, since information regarding the actual crane usage is available. Similarly, existing programs can be updated after, say, 10 – 15 years of use to better adapt to actual crane usage. For instance, some ports experience a much heavier than predicted usage, in which case the inspection intervals should be decreased. Since the fatigue damage is proportional to the third power of the stress range, a crane that regularly lifts loads heavier than originally expected will experience greatly accelerated fatigue damage.

Assessment Process

A structural maintenance program for an older crane should consist of a thorough condition survey by a structural engineer, reviewing the usage history, calculating stress levels and cumulative damage for all connections, developing an NDT manual, calculating inspection intervals, performing NDT, repairing any cracks, and improving connection details.

As an option, the remaining useful structural life of the crane could be estimated based on the past usage. From this estimate, a crane owner gains information to better assess the future usage. For instance, an owner could better decide whether it makes sense to increase the outreach or lift height of a crane based on this data.

Typical Problems—Details, Details …

Some welded details are more likely than others to develop cracks. Two such details are discussed here.

Attachments

Reliability depends on details. An otherwise proper design can be dramatically degraded by carelessly adding attachments for walkways, conduit, and mechanical and electrical equipment. See http://www.liftech.net/LiftechDesignNotebook/strucdetails.pdf for methods of avoiding poor details. For example, the expected life of the good detail shown in Figure 5 is 2.5 times or more greater than that of the bad detail shown.

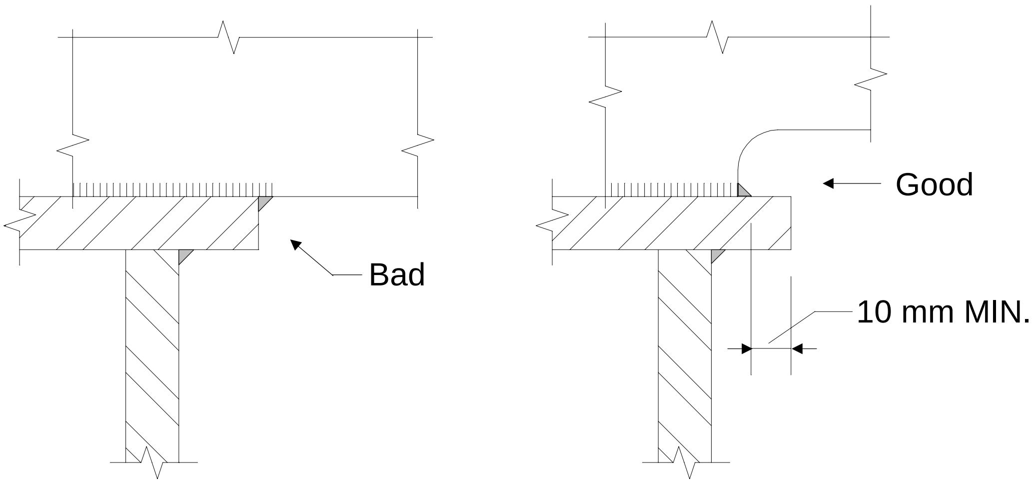

Figure 5: Example of a bad and a good welded detail

Forestay Connections

Forestay connections are often troublesome. Due to wind and gantry motion, forestays swing about the weak axis, parallel to gantry travel. Figure 6 depicts a crack in the connection between a let-in forestay gusset plate welded to the top flange of the boom. The "flexure distance" between the welds connecting the gusset plate to the top surface of the boom flange and the forestay boss plate was too small. As the boom swings, there is effectively a stress concentration caused by the hard spot directly under the boss plate. A fatigue crack started at the toe of the boss weld and propagated across the gusset plate. The same detail on another crane resulted in failure. We typically recommend a 5t flexure distance, where "t" is the thickness of the flexing gusset plate, to avoid this type of damage.

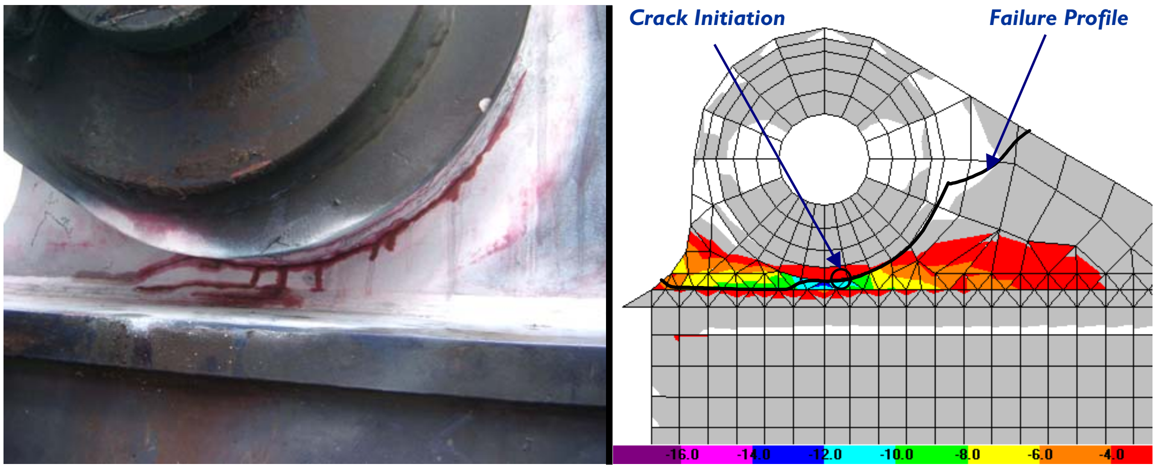

Figure 6: Forestay fatigue crack showing a picture of the crack on the left and the finite element analysis on the right.

FURTHER INFORMATION

For further information regarding structural fatigue, including this and other papers, presentations, and references, visit Liftech's website at:

http://www.liftech.net/lpublications_maintenance.html

REFERENCES

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Rolfe, Stanley T. and Barsom, John M., *Fracture and Fatigue Control in Structures*, Prentice-Hall, 2nd ed., 1987.

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