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NONDESTRUCTIVE EVALUATION OF CRANE STRUCTURES

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NONDESTRUCTIVE EVALUATION OF CRANE STRUCTURES

Overview

Welded steel structures always contain undetectable cracks usually at welded joints. When these joints are subjected to fluctuating stresses beyond a very small value, the cracks grow. This is fatigue crack growth. The allowable stress levels used in the design of cranes take the phenomenon into account. Allowable stress levels are determined by statistical analysis of laboratory tests of typical details subjected to hundreds of thousands of cycles of stress fluctuation. Allowable values are intended to provide a reliability of 97.5%. This means that in laboratory tests, 2.5% of the specimens fail at stress levels below the allowable. Since the test results show considerable scatter, a probabilistic rather than a deterministic approach must be taken in determining design values. There is always fatigue crack growth and a significant chance of fatigue failure.

There are no recognized crane specifications used in the world today that require stresses to be so low that fatigue crack growth will not occur on a random basis. Eventually, fatigue cracks become large enough to be detectable by means of nondestructive testing methods, i.e., MT, UT or DPT. Some cracks are detectable by visual inspection before fracture is likely. Even if fracture occurs, in many cases the remaining elements of the structure will prevent serious damage provided the crane is taken out of service and repaired.

Periodic inspections should be made to detect fatigue cracks before they grow to a critical size. Fatigue cracks usually start at discontinuities formed by welds, notches or holes (References 2 and 3). Typical stress distributions at welds are shown in Figure 1. Typcial fatigue crack locations are shown in Figure 2. Wrap-around welds, shown in Figure 3, are particularly likely to crack. Although wrap-around welds are prohibited by Reference 1, they are sometimes used as seal welds.

When a crack is found, repair is necessary. Restoring the structure to its original condition is always acceptable. Changing geometry by means of cutting and grinding may be best.

Fatigue Crack Growth

All steel structures contain fatigue crack starters. These flaws are developed during initial rolling, welding or cutting. The flaws may be microscopic or macroscopic. Figure 4 shows a typical crack, the elastic distribution of stress near the crack tip and the plastic zone at the crack tip.

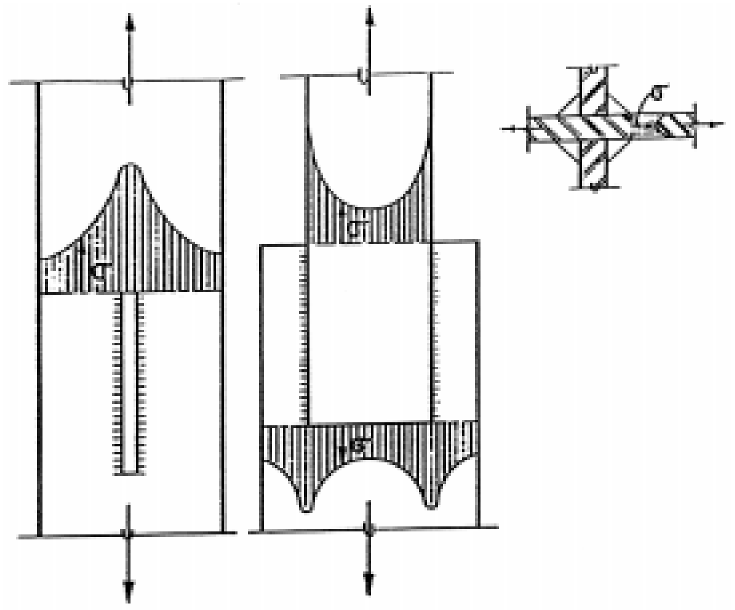


Figure 1: Typical stress distribution at welded joints

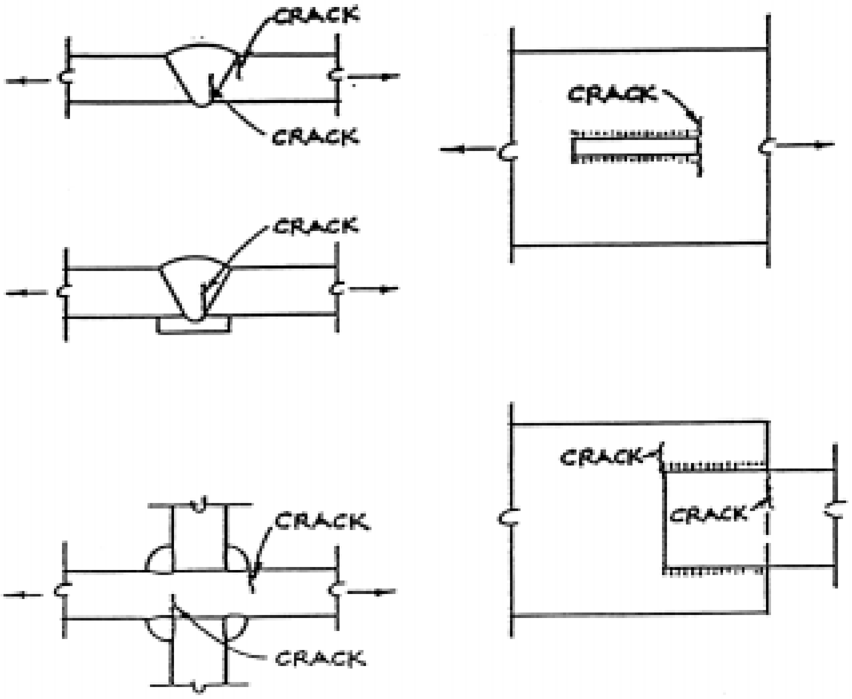


Figure 2: Typical fatigue crack locations

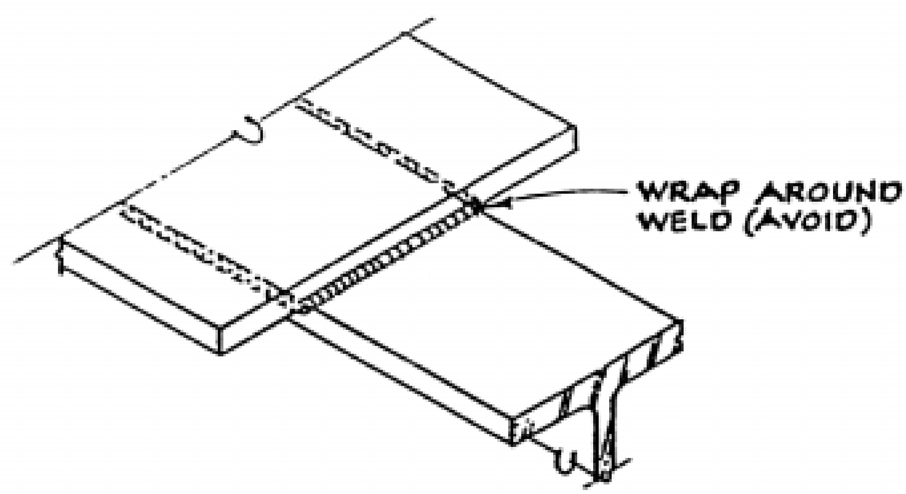


Figure 3: Typical wrap around weld

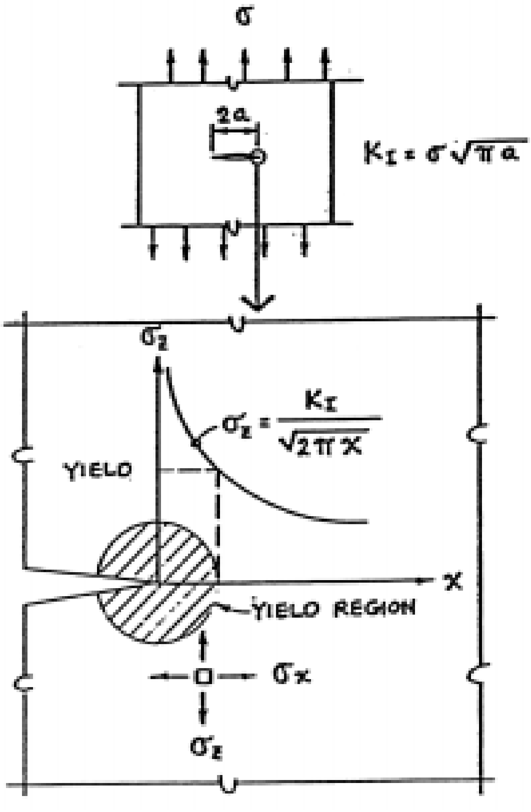


Figure 4: Elastic stress at crack tip

The stress in the vertical z direction is:

$$\sigma_z = K_I / \sqrt{(2\pi\ x)}$$

where σ_z = the stress in the z direction varying along the x axis

K_I = the stress intensity factor

x = the distance from the tip of the crack

Notice when x = 0, the theoretical elastic stress is infinite. Since the steel has a finite yield strength, a yield region is developed at the crack tip. If the crack size, 2a , is below a critical value, a single application load causes the yield zone to develop and the structure deforms without failure. If the load is reduced and then reapplied, the fatigue crack will grow as shown in Figure 5. The tip of the crack always advances perpendicular to the direction of principal stress. Examination of the crack surface reveals beach marks at the limit of crack growth with each application of load.

The distance the crack grows with each cycle is called the crack growth rate. It is measurable in inches per cycle. Crack growth rate can be divided into three regions (Reference 4):

Region 1: Crack growth rate is very small. The cracks are microscopic and are difficult to detect. This is the initiation region.

Region 2: The cracks have become large enough to become detectable and their growth can be observed.

Region 3: The cracks have become quite large. The rate of growth is rapidly increasing. Eventually, the crack is so large that the energy released due a unit area increase in crack size is more than the energy absorbed due to the same unit area increase in fracture surface and the detail becomes unstable and brittle fracture suddenly.

Obviously, one of the two purposes of nondestructive inspection is to detect the crack while it is in Region 2.

The fatigue crack growth rate is dependent on the stress intensity factor and for steels used in crane structures is independent of the yield strength and fracture toughness of the material. Higher strength steels can be subjected to higher nominal stresses resulting in higher stress intensity factors and more rapid fatigue crack growth.

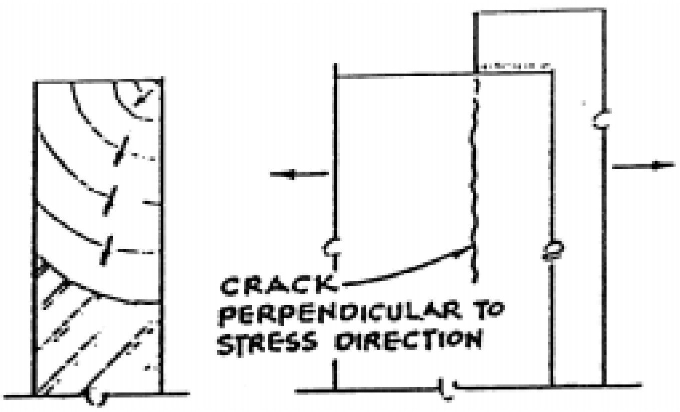


Figure 5: Fatigue crack growth

Stress Intensity Factor

For a particular steel, the crack growth rate depends on the stress intensity factor, K_I. The stress intensity factor is not a stress concentration factor, but rather a measure of the energy released as the cracks grows. At first, the concept of stress intensity is difficult to understand. Equation for stress intensity is:

$$K_I = c\sigma\sqrt{(\pi a)}$$

where c = a constant, a function of the detail and crack geometry

σ = the nominal size

a = the crack size, inches

Brittle Fracture

Visualize the crack in Figure 6 having size a and subjected to stress σ. When the crack grows by a small amount, the element deforms very slightly. The surface subjected to stress will deform slightly and the applied stress will do work on the element. The amount of energy released per unit increase in crack area can be calculated by fracture mechanics.

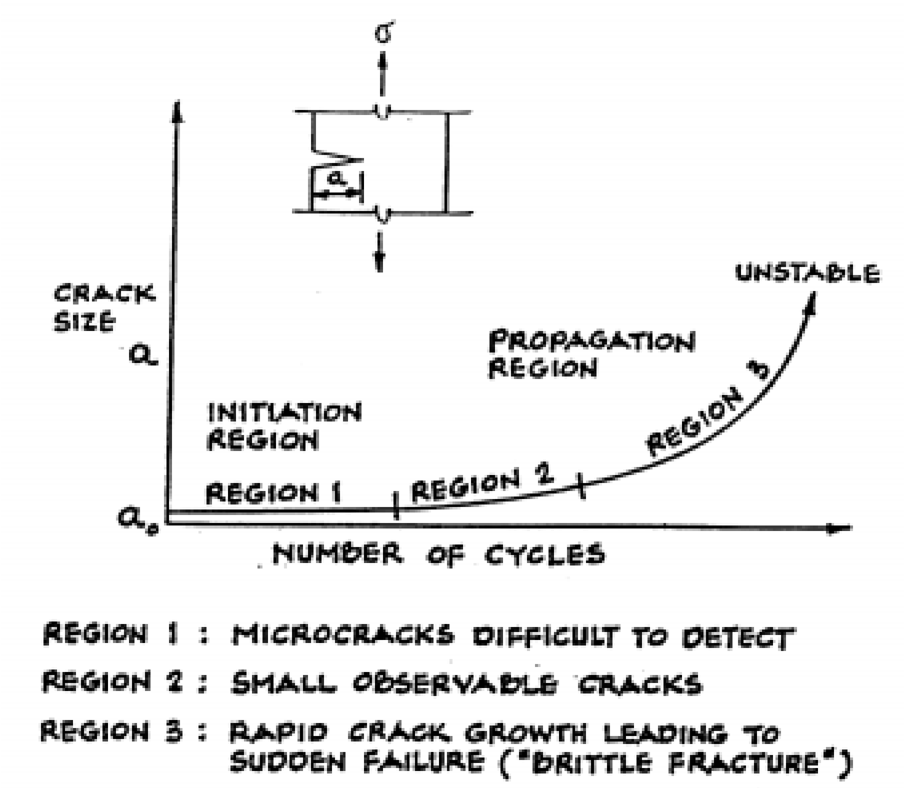


Figure 6: Crack growth rate

In order for the structure to be stable, the energy released due to crack growth must be balanced by the energy absorbed due to the fracture of the material at the crack tip. If the energy released due to crack growth exceeds the energy absorbed due to the fracture of material, the crack will grow thousands of feet per second. "Brittle fracture" will occur without warning.

Brittle fracture failure is significantly different than ductile failure. The fracture surface is flat showing cleavage failure. There is little, or no, shear lip. The average stress level may be significantly below the yield stress although yield stresses will occur at the crack tip. The atoms separate during cleavage failure rather than slide by one another as during general yielding.

Fracture Toughness

Fracture toughness measures the material's ability to resist brittle fracture. As the stress intensity K_I is a measure of the energy released per unit area increase in crack surface, the fracture toughness material K_{IC} is the measure of the energy absorbed per unit area increase in crack surface. Fracture toughness is determined by test.

The fracture toughness depends on many factors including grain size and chemical composition. The rate of loading and the test temperature also affect fracture toughness. The higher the rate of loading and the lower the temperature, the lower the fracture toughness. Increasing the yield or ultimate strength of the material does not necessarily increase the fracture toughness.

The compact tension test measures fracture toughness. A typical test sample is shown in Figure 7. A more economic test, the Charpy V-Notch test, may be used to evaluate fracture toughness although it is not a fracture toughness test. A correlation between energy absorbed in the CVN test and fracture toughness has been developed and is frequently used for determining the acceptability of materials. A typical relationship between compact tension and CVN tests is shown in Figure 10. A typical CVN sample is shown in Figure 8. Typical results for compact tension and CVN tests are shown in Figures 9A and 9B. Notice for a given temperature, the static loading results in higher fracture toughness than the dynamic loading. Also notice that increasing the temperature increases fracture toughness.

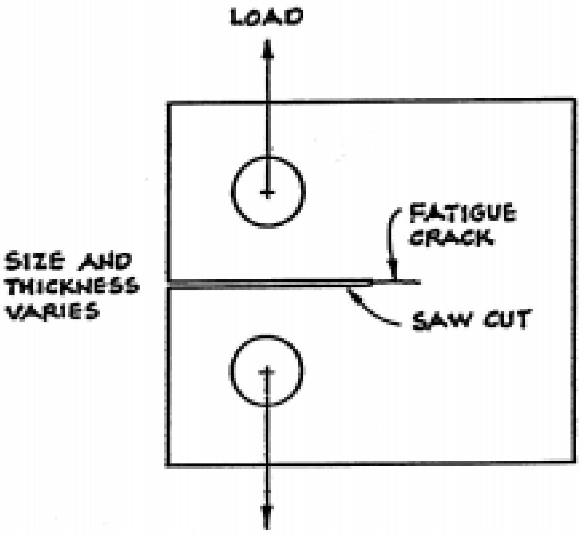


Figure 7: Compact tension test

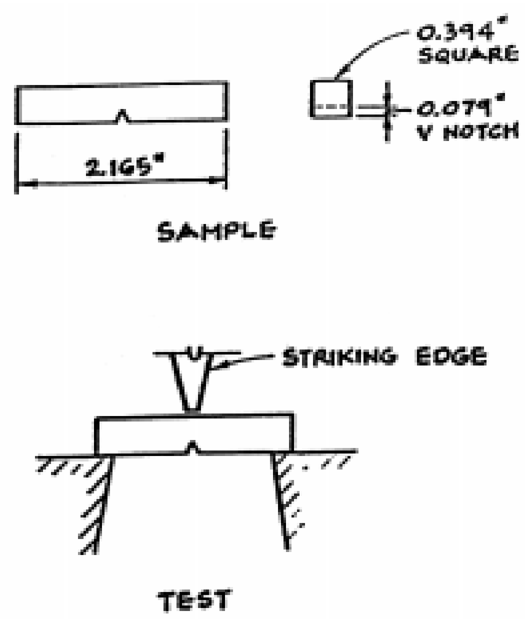


Figure 8: Standard CVN test

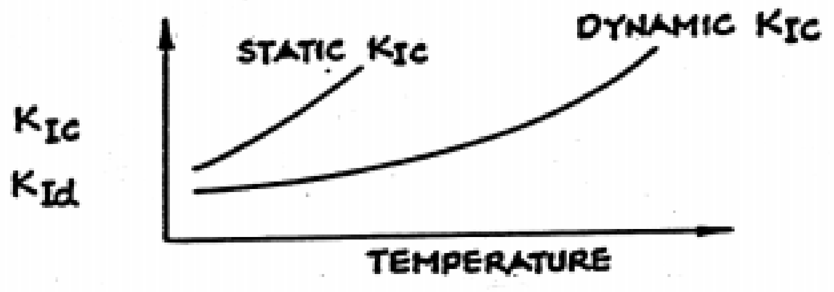


Figure 9A: Temperature and loading rate effects on K_{IC}

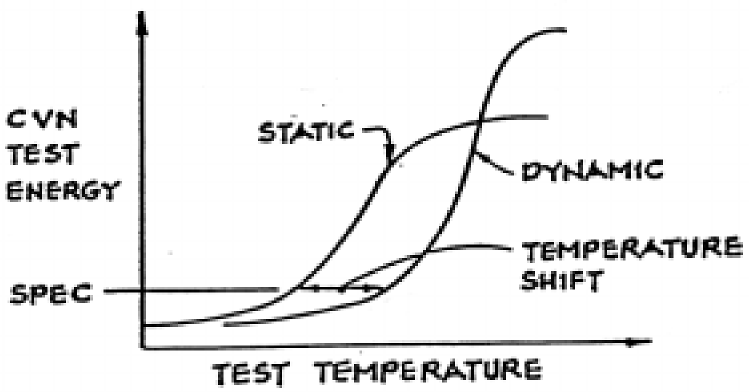


Figure 9B: Temperature and loading rate effects on CVN energy

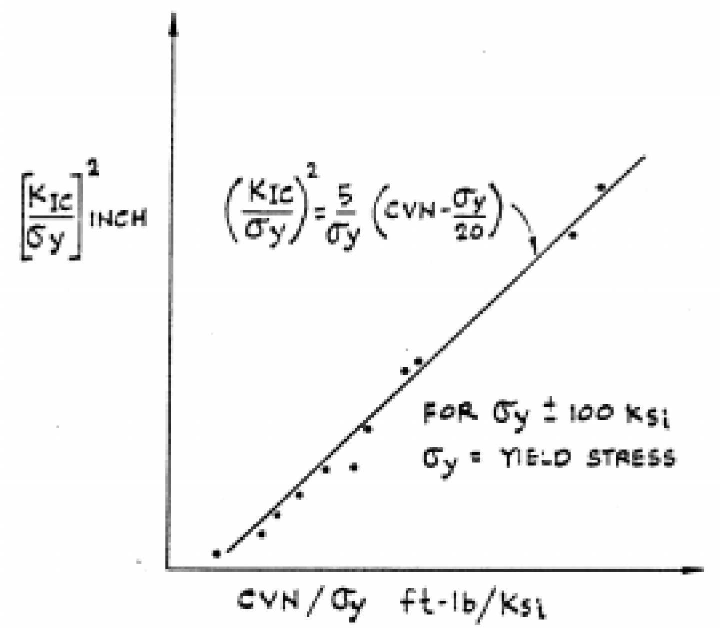


Figure 10: K_{IC} and CVN energy relationship

Material Specifications

In the U.S., steels used for cranes and bridges usually comply with requirements of ASTM A709-88a. Table 1 shows some of the requirements of this specification for fracture critical members.

The zones refer to different service temperatures.

Zone	Service Temperature °F	Test Temperature °F Steel Grade		
1	Above 0	36F	50F	100F
2	-1 to -30	70	70	0
3	-31 to -60	40	40	0
		10	10	-30

The CVN test loading is dynamic. Since the structure is assumed to be subjected to static loading rather than dynamic, the test temperature is higher than the service temperature. The higher test temperature which increases absorbed energy is used to compensate for a higher rate of loading which decreases test energy. The attempt is that these two effects will balance each other. The strain rate for static loading is about 10^{-5} inches per inch per second; for dynamic loading, it is about 10 inches per inch per second.

For bridges, loads are static. Although cranes may be either static or dynamic, it is common practice to consider the rate of loading on cranes to be static. The higher energy requirements for higher strength steel takes into account that more fracture toughness is needed when stress intensity factors are higher. If 36F steel is specified and the yield strength is high, say 50 ksi, the requirements for the CVN energy should accordingly be increased. Notice that the extracted table is for fracture critical members.

Grade	Thickness and Joining Method	Minimum Average Energy[B], ft-lbf		
		Zone 1 70 degree F	Zone 2 40 degree F	Zone 3 10 degree F
36F	to 4” incl	25	25	25
50F[C]	to 4” incl, mechanically fastened	25	25	25
	to 2” incl, welded	25	25	25
50WF[C]	to 4” incl, mechanically fastened	25	25	25
	to 2” incl, welded	25	25	25
	over 2” to 4” incl, welded	30	30	30
100F[D], 100WF[D]	to 4” incl, mechanically fastened	35	35	35
	to 2-1/2” incl, welded	35	35	35
	over 2-1/2” to 4” incl, welded	45	45	E

[A] Fracture critical members or member components are defined by the American Association of State Highway and Transportation Officials (AASHTO) as tension members or tension components of members whose failure would be expected to result in collapse of the bridge.

[B] The CVN-impact testing shall be “P” plate frequency testing in accordance with Specification A 673 except tests shall be on each end of each plate. For material greater than 1-1/2” in thickness, the required test temperature shall be reduced by 20 deg. F.

[C] If the yield point of the material exceeds 65 ksi, the testing termperature for the minimum average energy required shall be reduced by 15 deg. F for each increment of 10 ksi above 65 ksi. The yield point is the value given on the certified “Mill Test Report.”

[D] The CVN-impact test temperatures shall be the following:

Zone 1 at 30 deg. F
Zone 2 at 0 deg. F
Zone 3 at -30 deg. F

[E] Not permitted.

Reference: ASTM A709-88a, page 668, Table 8.

Table 1: Fracture critical[A] impact test requirements

Stress, Flaw Size and Fracture Toughness Relationship

Figure 11 shows a typical crack on the edge of a plate and the relationship between the nominal stress, size of the crack and the material toughness. The stress intensity factor increases with increasing stress and crack size. Once the stress intensity exceeds a critical value, K_C, the crack becomes unstable and brittle fracture occurs. Since lowering the temperature lowers the toughness and increasing the rate of loading increases the toughness, the boundary between stable and unstable behavior is not fixed. The general boundary shape will remain the same as fracture toughness varies, but the position of the curve will move diagonally away from the origin as the temperature rises and the rate of loading decreases and toward the origin as the temperature decreases and the rate of loading increases.

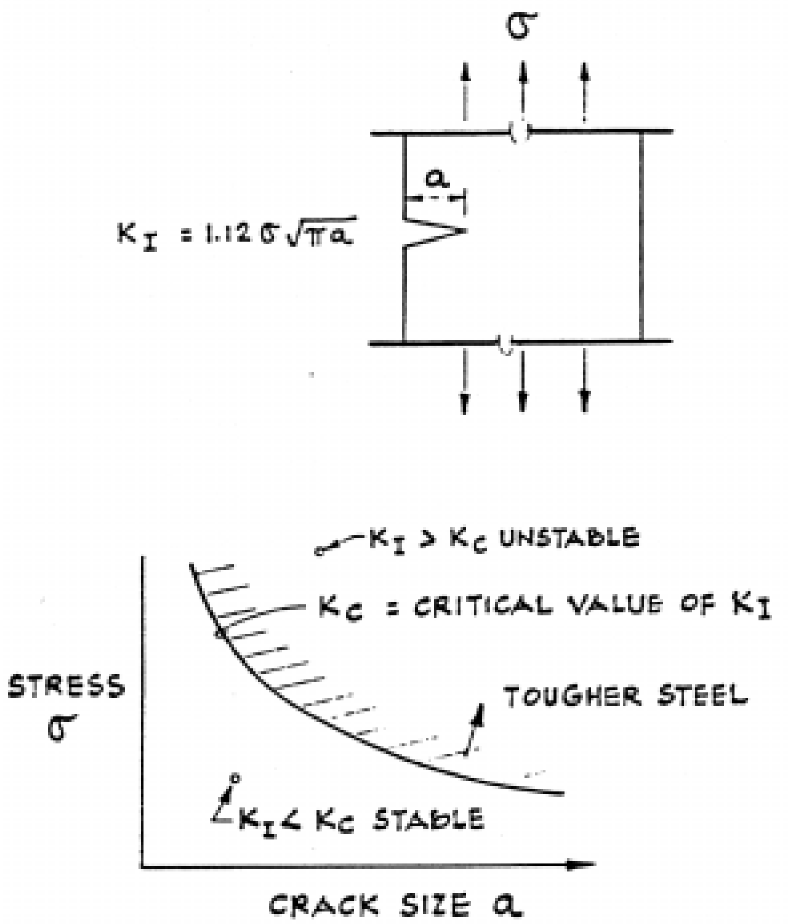


Figure 11: Stress, flaw size, and material toughness relationship

Design Approach

The design of a crane subjected to fluctuating stresses is more complex than design of a structure subjected to static stresses. The fatigue strength of the structure depends on many more factors than does the static strength. The number of fluctuations of stress, magnitudes of the fluctuations, selection of the appropriate weld detail and importance of each detail relative to the structural integrity of the crane all influence the design.

The uninitiated usually believe the crane should be designed to last forever with no limits on its fatigue life. Unfortunately, this is impossible. Real crane structures will experience fatigue crack growth and if used indefinitely without inspection will eventually fail. The designer and operator should both recognize this.

Allowable fatigue stresses are determined from statistical analysis of test data. The test sample is subjected to fluctuating stresses similar to those shown in Figure 12. The stress range is varied, data is collected and an allowable stress range envelope is determined as shown in Figure 13. Various details are tested and appropriate stress levels are found for each. Figure 14 shows some typical details and allowable values (Reference 5).

Design specifications consider that certain details are more susceptible to fatigue cracking than others. Higher stresses are allowed for better details. Theoretically, a structure could be designed so that a detail which performs very well under fluctuating stress is just as likely to develop cracks as one that performs poorly. In practice, static stresses often govern the strength of many members and details that can withstand fluctuating stresses well are less likely to develop fatigue cracks.

Typically for members governed by fatigue, the probability of fatigue failure during the design life is 2.5%. This is much larger than the probability of failure used for a typical structure designed to resist static forces. Redundancy may be used to improve reliability. Redundant elements are those where if one element should fail, the other can carry the load. Two elements are more reliable than one because once a fatigue crack reaches a critical size and brittle fracture occurs, the brittle crack will not enter the second element.

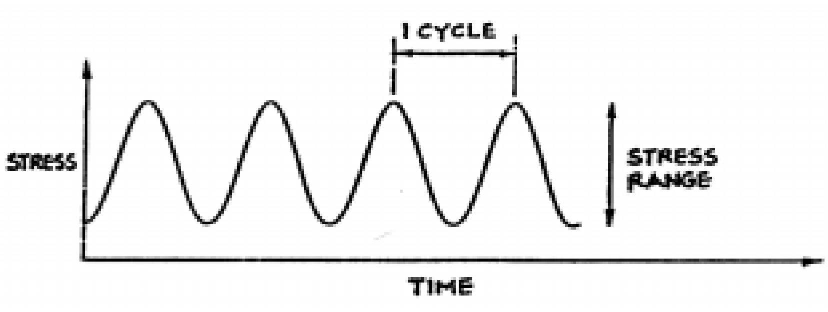


Figure 12: Typical test fluctuating stress

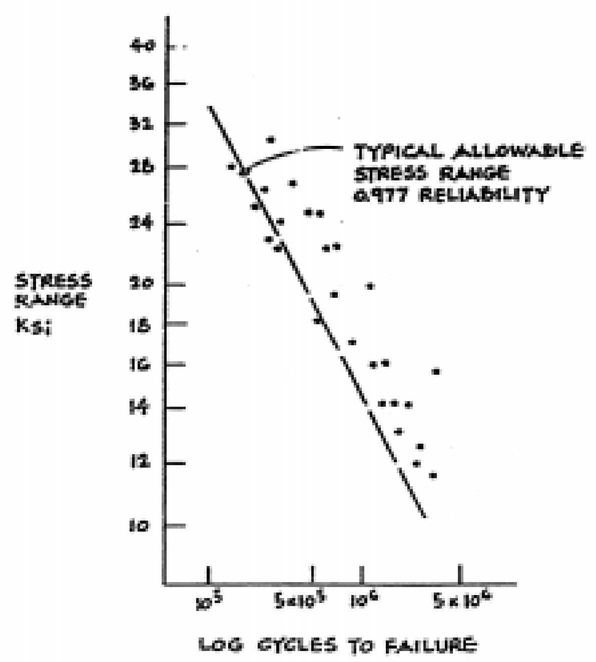
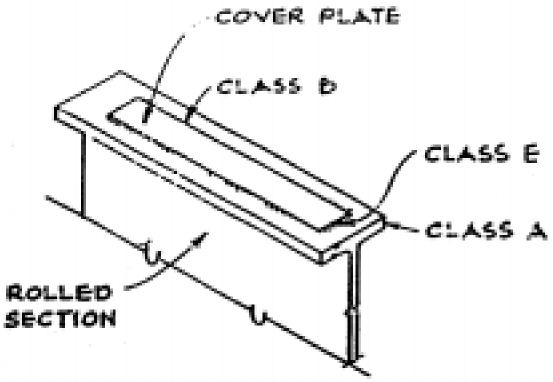


Figure 13: Typical stress range cycles to failure relationship



AASHTO FCM

ALLOWABLE
STRESS RANGE 2×10^6 CYCLES

CLASS	STRESS Ksi
A	24
B	16
E	5

Figure 14: Effect of welds on allowable stress

The opposite of increasing reliability through redundant elements is decreasing it through a series of elements as in a chain. If the reliability is .98 and the chain consists of tow links, the reliability is $.98^2$ or .96. If the chain has ten links in series, the reliability is only .82. This means that the probability of failure is nearly one in five. This potential for extremely low reliability is not recognized in the design standards and occasionally is not recognized by the designer. Occasionally, cranes are designed with a series of elements forming a chain significantly increasing the probability of failure. Each link becomes as important as each member and deserves as much attention.

Fracture critical members of component members are tension members or tension components of members whose failure would be expected to result in collapse of the crane. Tension components of the crane consist of components of tension members and those portions of flexural members that are subjected to tension stress. Any attachment having a length in the direction of tension stress greater than 4″ that is welded to a tension component of a fracture critical member should be considered part of the tension component and also be considered fracture critical (Reference 6). The ASTM A709 material specification recognizes the distinction between FCM's and non-FCM's. Some design specifications also recognize the distinction.

Fracture Control Plan for Existing Cranes

The purpose of a fracture control plan is to increase the reliability of the crane. Since the structure is existing, the option of doing this by controlling welding techniques, increasing fracture toughness, and using fatigue resistant details is unavailable. Improving reliability can only be achieved through detection of fatigue cracks and making appropriate improvements and repairs.

A fracture control plan should include instructions describing what to inspect, what methods to use and how to report the results of the inspection. Fracture critical members should be identified. The likely location of cracks can be determined using the principles of fracture mechanics. If the stress spectra are known, the cumulative damage at each detail can be calculated:

$$D = \sum(\Delta\sigma_i)^m n_i$$

where D = applied

$\Delta\sigma_i$ = stress range for the i fluctuation

n_i = number of applications of $\Delta\sigma_i$

m = exponent from test data, usually 3

The allowable cumulative damage can be found by:

$$A = \Delta\sigma^m N$$

where A = allowable cumulative damage

$\Delta\sigma$ = allowable stress ranges for N cycles

N = cycles in specification

Figure 15 shows a typical stress spectra. The stress range and cycles can be counted using the reservoir method (Reference 7).

The relative cumulative damage, R, can be determined by dividing the applied cumulative damage, C, by the allowable cumulative damage, A. Usually, the allowable cumulative damage for fracture critical members is on the order of 1/3 that for non-fracture critical members. When the relative cumulative damage is calculated, the reliability of each joint can be evaluated and an inspection interval can be determined to maintain the degree of reliability desired. Liftech Consultants usually recommends inspecting the crane when R reaches 0.30 to obtain a reliability of .999, a significant improvement over the typical design reliability of .975.

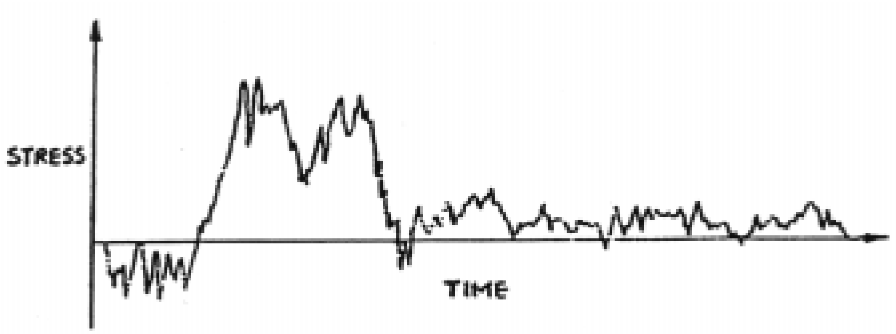


Figure 15: Typical working crane fluctuating stress

The overall reliability analysis should include the effect of details in series.

Prior to about 1975, most steels for cranes were not tested for fracture toughness. Even today, many steels used in cranes are not tested. When possible, existing material should be sampled and CVN tests made. When this is impractical, chemical analysis may identify poor steel since typically the fracture toughness of the material is related to the chemisty.

Some Common Misconceptions

Test load verifies the structural integrity of the crane (not true).
The load test merely demonstrates the ability of the crane to withstand static or dynamic loads under conditions at which the tests are made. Recall the stress intensity factor is a function of temperature and rate loading. Even if the rate of loading and the temperature are at extremes, the crack size is not. Cracks only get larger. A crane that satisfactorily completes a load test may not be safe against brittle fracture.

Lamellar tearing is "brittle fracture" (not true).
Lamellar tearing shown in Figure 16 is a separation in the parent or base material caused by thru-thickness strains induced by weld shrinkage. Under the conditions of high restraints, localized strains due to weld metal shrinkage can be many times higher than the yield point strains, whereas stresses due to design loads are only a fraction of the yield point. The strain due to applied loads are not of primary concern in causing lamellar tearing. No cases are known of lamellar tears being initiated or proprogated by design loads (Reference 8). Although lamellar tearing is a failure due to lack of ductility, it is not "brittle fracture" and is unrelated to fatigue or the other issues discussed above.

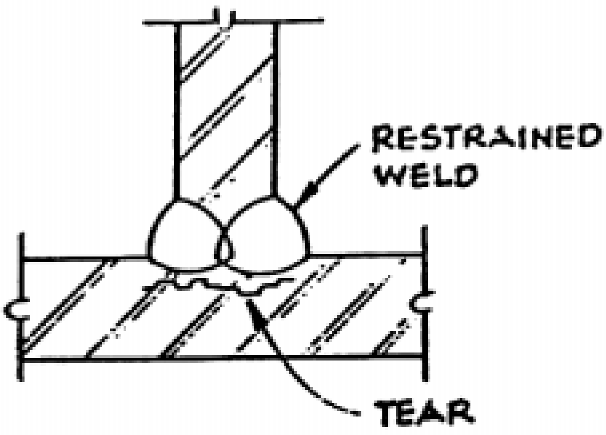


Figure 16: Lamellar tearing (not "brittle fracture")

Adding material improves the strength of the structure (not true).
This can be seen by the allowable stress levels. The allowable stress at the end of a cover plate is only a fraction of the allowable stress beyond the cover plate. When fatigue cracks develop in a detail which is less severe than the end of an attached plate, adding a cover plate is not an improvement. Though the structure will carry the load temporarily, its life will be shorter than that of the original structure.

Conculsion

Fatigue crack growth and ultimate "brittle fracture" is a threat to all cranes. Even well designed cranes meeting all recognized standards will develop fatigue cracks on a random basis. If unchecked, these cracks will grow and may cause structural failure. A suitable fractue control plan based on the principles of fracture mechanics will reduce the chance of brittle fracture.

Through cost effective inspections, reliabilities can be greatly increased and the life of the crane can be extended well beyond its original planned life.

References

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