Structural Design

design issues for structural engineers

AISC and Damage Tolerance Approaches

Part 2

By Paul W. McMullin, S.E., Ph.D.

Paul McMullin is a Founding Partner at Ingenium Design in Salt Lake City. He is an Adjunct Professor and the lead editor of the Architect's Guidebooks to Structures *series. Paul can be reached at* ***Paulm@ingeniumdesign.us****.*

Continuing on the foundation established in the last article (STRUCTURE, August 2016), let's now look at two fatigue design methodologies: AISC and Damage Tolerance. AISC is based on the safe life philosophy – if the engineer keeps the stresses low enough, the structure will perform adequately. It also assumes cracking occurs at the end of the structure's life. Damage Tolerance approaches the problem from the opposite perspective. It assumes the structure inherently has discontinuities in critical locations from the first day it is in use. These discontinuities are below the inspection threshold, but will grow as time goes on. The engineer designs toughness, redundancy, and inspection into the structure. This is done in a closed loop system, receiving feedback at critical stages in the structure's life.

AISC Fatigue Design

General Concepts

AISC fatigue design methodology is very similar to that found in AASHTO and AREMA. Key concepts of AISC fatigue design include:

- Fatigue design is not required if the structure will see less than 20,000 cycles, or when the stress range is below the threshold F_{TH}.
- Use service loads (allowable stress load combinations).
- The AISC provisions assume suitable corrosion protection.
- Calculating the number of cycles can at best be a guess. Talk to the operator and be conservative.

Stress Calculation

When calculating stresses, the following need to be considered:

- Use an elastic stress analysis.
- Include prying effects in bolts.
- Include the effect of eccentricities.

AASHTO – American Association of State Highway Transportation Officials
AISC – American Institute of Steel Construction
AREMA – American Railway Engineering and Maintenance-of-Way Association

- Ignore the stress concentration (the table values take this into account).

Stress range is calculated considering only the fluctuating stresses, not total stresses. Permanent stresses, such as dead loads, do not contribute to the fatigue stress range.

For example, if there is a 5 ksi cyclic load in combination with a 15 ksi dead load (*Figure 1a*), the stress range is only 5 ksi. It is possible to make the mistake that the stress range is 20 ksi, which would lead to a substantially heavier design.

Looking at another condition, if a 10 ksi fully-reversing stress exists but no permanent loads are present (*Figure 1b*), the stress range is 20 ksi. This is because we are adding peak-to-peak stresses. If we took the stress from zero to peak, we would underpredict our stress range by a factor of two.

Allowable Stress Range

Once the engineer has accurately calculated the stress range, they need to compare it to the allowable stress range. There are two ways to do this: calculate the stress range based on the number of cycles, or limit the stress to the threshold. A description of both methods follows.

Using an estimate of the number of cycles, the allowable stress range, F_{SR}, can be calculate based on the following equation:

$$F_{SR} = \left(\frac{C_f}{n_{SR}}\right)^{0.333} \geq F_{TH}$$

Where

C_f = factor from AISC tables
n_{SR} = number of cycles in design life
F_{TH} = fatigue threshold stress range

If the design of the structure is based on the fatigue threshold stress – which may be prudent for structures that may be in service well beyond their service

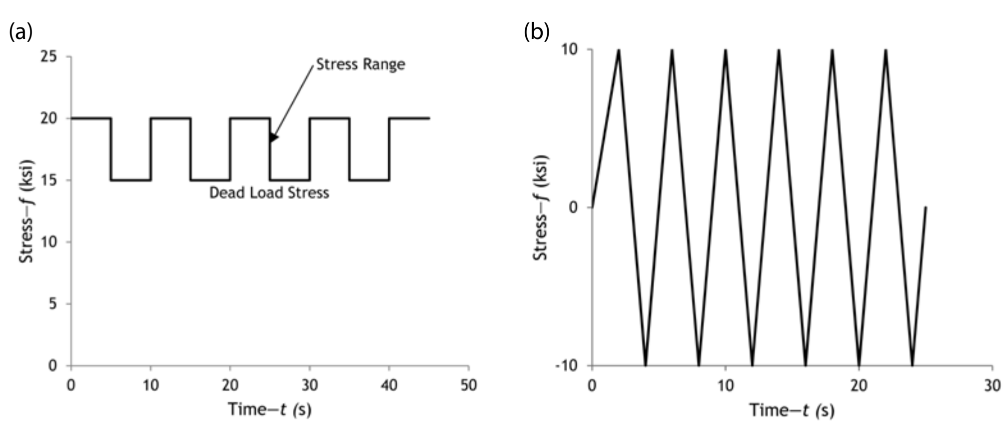


Figure 1. Stress range examples for (a) high permanent stress, and (b) fully reversing stresses.

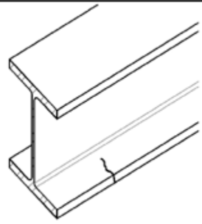
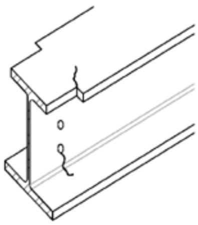
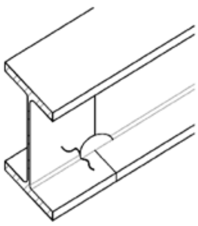
Sketch		Description	Stress Category	Constant C_f	Threshold F_{TH}
1		Base metal	A	250×10^8	24
2		Holes and re-entrant corners	B	120×10^8	16
3		Rolled sections with weld access holes	C	44×10^8	10

Figure 2. Representative AISC, AASHTO, or AREMA fatigue design data (after AISC).

life – the engineer simply sizes the component, so the stress range is below the threshold value from data similar to that shown in *Figure 2*. While this doesn't ensure an absence of cracking for the life of the structure, it is a place to start and can be combined with a robust inspection plan to ensure safe performance.

Damage Tolerance Approach

Damage tolerance flips the traditional design approach on its head. Rather than saying everything is great if the stresses are small enough, it assumes there is already a problem, and we need to design for it. The engineer must assume there is a discontinuity in the most critical point in the structure, and design for it. Below is an outline of how this is accomplished.

1) Inspect the critical locations in the structure after construction
2) Assume an inherent discontinuity at least the size of the threshold of detection
3) Use fracture mechanics to predict the critical crack size
4) Use fracture mechanics correlations to predict how long it will take the crack to reach its critical size
5) Inspect at intervals that can catch the crack before it reaches its critical size
6) Repair cracks or retire the structure/element from service

Fracture Mechanics

Before A.A. Griffith proposed his theory on crack propagation in glass, and Irwin made it useable and extended it to other materials in 1948, design techniques could not explicitly consider cracks. No one could analytically predict at what size a crack would propagate unstably.

Fracture mechanics received its start while Griffith was trying to understand the effect of surface treatment on the strength of cyclically loaded metal parts. To reduce the potential confusion plastic deformation might cause, he began testing glass because of its "brittle" behavior at room temperature. From his investigations from 1918 to 1920, Griffith proposed that a crack would propagate when the change in elastic energy with respect to crack length equaled the energy required for that increment of growth. From this concept, for a linear elastic material, Griffith derived the following relationship.

$$\underbrace{\sigma\sqrt{\pi c}}_{K} = \underbrace{\sqrt{2E\gamma}}_{K_c}$$

Where

σ = far-field stress
E = elastic modulus
γ = surface tension
c = half crack length of a center cracked specimen

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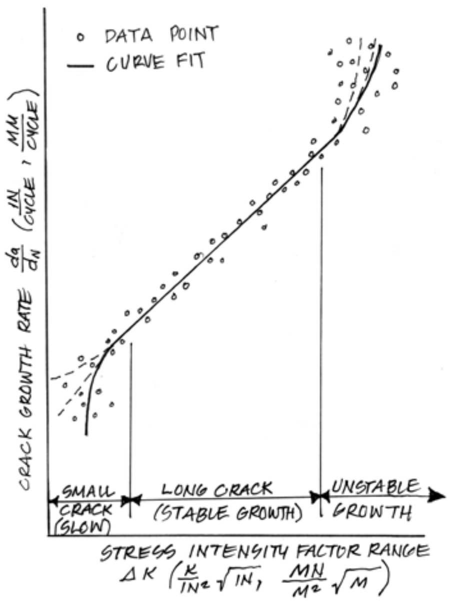

Figure 3. da/dN versus ΔK fatigue correlation curve.

When the left side equals the right side, fracture will occur. The only challenge with solving the equation is that gamma, γ, is difficult to obtain. So challenging, in fact, that nobody used the Griffith expression until George Irwin modified it while at the Naval Research Lab decades later. Irwin proposed that the right-hand side of the Griffith Equation could be experimentally determined, and called it fracture toughness. When the left-hand side of the Griffith Equation, known as the stress intensity factor K, equals the toughness K_c, the crack will propagate unstably (approximately ⅓ the speed of sound in the material). From this concept, many analysts have developed stress intensity solutions for a wide variety of geometry and loading conditions. These are available in a multitude of handbooks.

These developments opened a new world in predicting fracture behavior. It was no longer based solely on experience, and engineers could predict the behaviors of structures that hadn't been built yet. Regarding the functional application of fracture mechanics, Irwin stated:

> *The practical importance of fracture mechanics appears when one asks how much of each remedy is needed in quantitative terms, or when one attempts to link together prior estimates of stresses, crack sizes, and material toughness so as to calculate in advance a service load which will be safe relative to fracture propagation.* (Irwin 1958, p. 557)

The power of fracture mechanics is that it tells the designer the size of a crack-like discontinuity that a structure can withstand before final instability. One can then predict how long it will take for a fatigue crack to reach the critical size. The safe life philosophy cannot do this.

Fatigue Correlations

Extending fracture mechanics to fatigue, the engineer can relate the change in crack length to stress intensity factor range per cycle. This is accomplished through a *da/dN* versus *ΔK* curve, like the one in *Figure 3*. The curve is based on test data and because it is related to change in stress intensity factor, can be extended to different component and crack geometries.

By curve fitting the data to an equation, rearranging so *da* and *dN* are on opposite sides of the equation, and integrating with respect to crack size *a*, we determine the total life. The distinct advantage of presenting fatigue data in this manner is it explicitly considers initial discontinuity size.

Inspection

Inspection is to damage tolerance as energy methods are to statics. It allows the engineer to know what a structure's initial discontinuity state is due to fabrication and evaluate changes as the structure's ages. Inspection is the feedback in a closed loop system. It is, therefore, critical that we have a rational and robust inspection plan.

The key components of any inspection plan are:

1) what to look for
2) when to look
3) how to look
4) where to look
5) how often to look
6) the threshold of detection
7) the probability of detection

Let's briefly review how to look, or inspection methods. Non-destructive test methods can be broken into two groups: surface and internal. Each group has a unique place and ability to find discontinuity.

1) surface
   a) magnetic particle
   b) eddy current
   c) liquid penetrant
2) internal
   a) ultrasonic
   b) radiographic

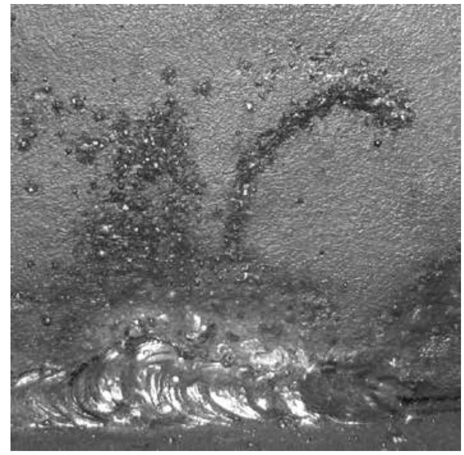

Figure 5. Arc strike on a structural steel member.

Magnetic particle and ultrasonic testing are the most common in civil structures to detect surface and internal cracks, respectively.

Coupling inspection technique with a threshold of detection, we can know what our initial crack size is for design. *Figure 4* shows the minimum and maximum crack sizes each inspection method can find.

Pulling damage tolerance together, we begin with design, which is based on an initial crack size, crack growth rate, and fracture toughness. We couple this closely to inspection, gaining feedback at key points in the structures life. This provides a clearer picture of what is going on, than just keeping our stresses low and hoping for the best.

Fabrication Considerations

Regardless of what design methodology we choose, prudent fabrication practice is key to well-performing structures. Let's review some key requirements from AISC and AWS D1.5 *Bridge Welding Code*.

AISC general fatigue requirements include:

- Remove transverse backing bars on full penetration welds. The author recommends removing all backing bars

Test Method	Discontinuity Sizes: Minimum (in)	Minimum (mm)	Maximum (in)	Maximum (mm)
Surface				
Liquid Penetrant	0.017	0.43	0.700	17.78
Magnetic Particle	0.039	0.99	0.237	6.02
Eddy Current	0.022	0.56	0.750	19.05
Internal				
Ultrasonic	0.014	0.36	0.265	6.73
Radiographic	0.024	0.61	0.729	18.52

Figure 4. Nondestructive testing crack detection thresholds.

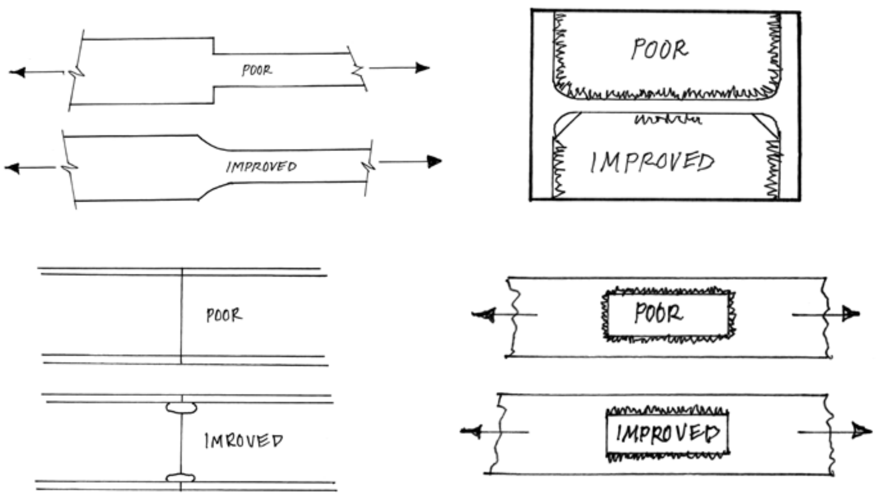

Figure 6. Poor and improved fatigue detailing examples.

– which can easily be accomplished by using copper or ceramic backing.

- Grind thermally cut edges to 1,000μin.
- Place a ⅜-inch radius on thermally cut edges.
- Pretension bolts.

AWS D1.5 requires the clear definition and requirements for the following:

- design
- workmanship
- technique
- procedure qualification
- inspection
- repair
- Fracture Control Plan for fabrication
  - contract documents
  - base metal
  - weld processes
  - consumables
  - procedures
  - certification & qualification
  - cutting
  - repair
  - straightening
  - tack welds
  - preheat & interpass temp
  - heat treatment
  - inspection

Remember, these are all fabrication requirements and do nothing to address in-service maintenance or inspection.

Two fabrication considerations are illustrative of the care the engineer needs to exercise in steel fabrication, hole punching and arc strikes.

When the fabricator punches holes, little cracks are left behind around the edge. Normally, this is not a problem. However, in fatigue sensitive structures, these cracks can grow. To address this, a fabricator can punch a hole smaller than the finished size, and ream to the final size or simply drill the holes.

When a welder accidentally drags the welding electrode across a steel part, it arcs and creates a trail of little puddles, like those in *Figure 5*. These leave behind a martensitic steel phase that is very hard and prone to cracking. Many great fatigue failures have started from such strikes. To correct them, we simply need to grind them out to sound metal and use magnetic particle testing to check for surface cracks.

Detailing

Let's end with a look at some detailing considerations. A notch in commercial construction often is not a problem, but in a fatigue sensitive structure it could be catastrophic. Let's look at four details, shown in *Figure 6* that with simple modifications can provide substantially longer fatigue life.

Notice how the changes center on smoothing out notches, reducing constraint, and lowering weld residual stresses.

Conclusion

This article has introduced fundamental concepts of traditional fatigue design and an alternate, more robust methodology, Damage Tolerance. When we couple initial crack sizes, toughness, fracture mechanics, and inspection, we are far better prepared to design for and evaluate cracks in our structures. We go from hoping for the best, to rationally predicting, monitoring, and repairing cracks in our structures – giving us more confidence in our engineering decisions. How nice is that?▪

For Reference

Irwin, G.R., (1958). "Fracture Mechanics." *Proc. Symposium on Naval Structural Mechanics*, VI, 557-594.