Fracture Case Studies

Part 3

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The previous two STRUCTURE magazine articles (*General Principles of Fatigue and Fracture, Part 1*, August 2016 and *AISC and Damage Tolerance Approaches, Part 2*, November 2016), reviewed the fundamental principles of cracking and how to design for fatigue and fracture. This article presents three case studies that illustrate how an engineer can use this guidance to address project challenges. The intent of this article is to move from the theoretical to the practical, and demonstrate that there is a realistic place for the more developed methodologies of fatigue and fracture mitigation.

Northridge Earthquake

The 1994 Northridge earthquake had a tremendous impact on the American Institute of Steel Construction's (AISC) steel code over the past 20 years. After the magnitude 6.7 (Mw) earthquake, inspectors discovered 1,300 fractured moment frame connections in 72 buildings. Naturally, this made many people uncomfortable.

To address the fracture issues, the SAC Steel Project (**www.sacsteel.org**) studied material behavior, connection geometry, and construction practices to figure out what happened and why it happened. Results of the project are widely published and infused throughout current AISC Seismic provisions.

One of the questions that came up during the studies was the effect of the welding backup bar. Field erectors preferred leaving them in place because they take time and money to remove. However, they create an inherent notch in the joint. This section uses fracture mechanics to study the impact that leaving the backing bar in place has on joint behavior, and what happens when it is fully fillet welded to the beam flange.

In the first condition, the backing bar is tack welded to the column flange and fused to the beam as the weld is deposited, illustrated in *Figure 1*.

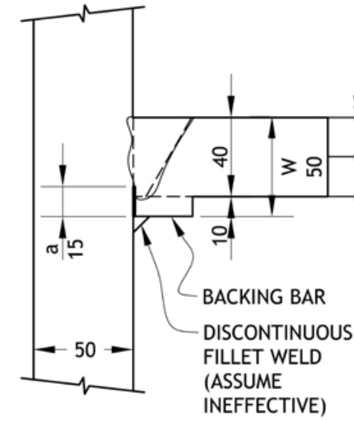

Figure 1. Beam to column flange weld in Pre-Northridge moment connection.

Note how the backing bar and any lack of fusion at the weld root creates a crack. Using fracture mechanics, one can plot the stress intensity K_I as a function of crack depth and far-field stress, shown in *Figure 2*. Using a fracture toughness of 50 MPa $(m)^{1/2}$ – a middle ground value – most of the stress intensities are greater for stresses in the yield range (250 MPa to 350 MPa). Even with twice the toughness, it still seems like a poor choice to leave the backing bar in place.

What happens when a continuous fillet weld is placed along the bar? Won't that take care of the problem? There now exists an eccentric crack condition. Looking at *Figure 3*, notice that about half of the stress intensity values are higher than the assumed toughness. There may be an argument to allow this condition. However, considering the possibility of lower toughness, the certainty of constraint near the web intersection, and the potential for the crack to grow due to low-cycle fatigue, it also seems imprudent to leave the backing bar in place.

In the end, a joint where the backing bar is removed, with the weld root gouged out and rewelded, can perform orders of magnitude better than one that has a crack-like lack of fusion in it from the backing bar. This conclusion is born out not only by the analysis but also by a rational view of the problem.

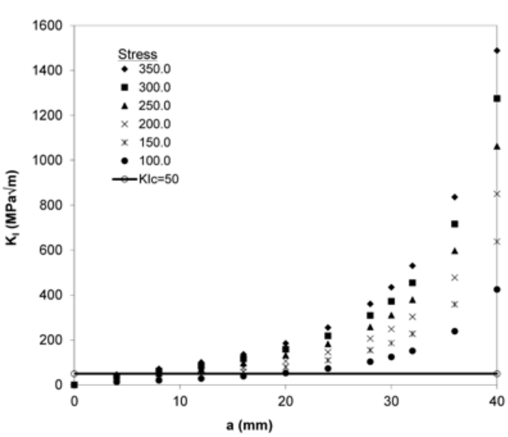

Figure 2. Tack welded stress intensity solution as a function of crack depth.

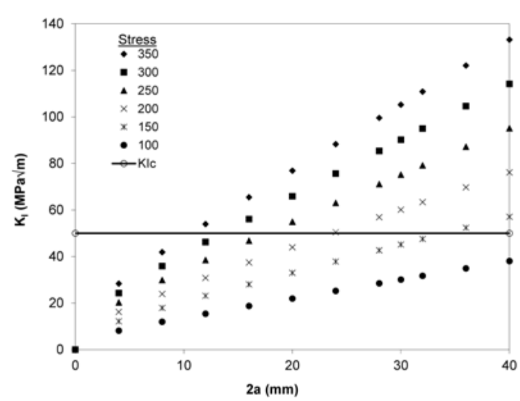

Figure 3. Fully welded stress intensity solution as a function of crack depth.

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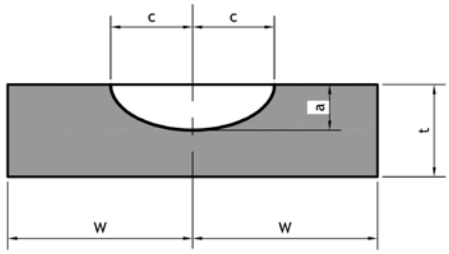

Figure 4. Assumed crack geometry in the tank wall.

Ammonia Tank

The question to answer, on a sizeable ammonia tank, is what stress corrosion cracks need to be repaired and which ones can be left alone. When steel is in contact with ammonia with very low oxygen content, cracks do not grow. However, cracks do grow in tanks when the ammonia is contaminated with air. The tank in question had been out of service for some time and had a number of stress corrosion cracks. The owner wanted to recommission the tank, and hence the project.

Utilizing API RP 579 *Fitness for Service*, the engineers on the project created crack ratio charts that let field crews know which cracks needed repair. Cracks under a certain size for a given aspect ratio, though detected, could remain in place.

The effort began by mining Charpy toughness data from material test reports. Using the master curve approach, the engineer correlated Charpy values to fracture toughness K_I values. The correlations are a function of thickness and Charpy energy values. This provided one side of the equation – the other being the stress intensity factor.

Utilizing this data, the engineer developed stress intensity solutions based on the basic crack geometry shown in *Figure 4*. These are from solutions in API 579. Selecting a crack length *2c*, a crack depth *a* is calculated. Doing this for numerous crack lengths, the curves in *Figure 5* and *Figure 6* are generated. Where the crack depth is greater than the tank wall thickness (*Figure 5*), a leak-before-break condition exists. This approach is good because the tank will leak before rupturing. However, for lower toughness material, like in the weld or heat affected zone, a break-before-leak condition existed (*Figure 6*). This is of more concern, given the lack of warning before catastrophic failure.

This analysis tells two things. In the base metal, long, shallow cracks need to be repaired, as a break-before-leak condition exists for aspect ratios (*a/2c*) less than 0.5. In the weld base metal, all cracks of a given size need to be repaired. The engineer can decide what crack size, for a given aspect ratio, needs to be repaired by choosing an acceptable safety factor.

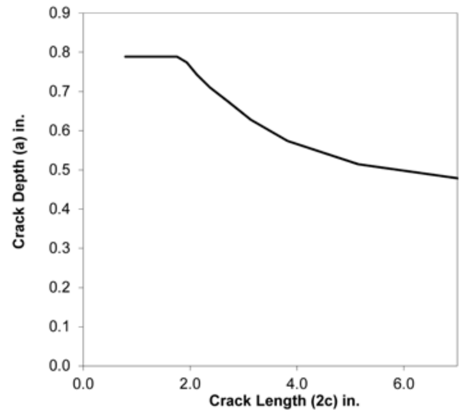

Figure 5. Critical crack size, a leak-before-break condition in the tank wall.

Finally, perhaps a third lesson: Not every crack is a problem and needs to be repaired.

Bridge Crane

The bridge crane in *Figure 7* was one of the dozens in the area that were decommissioned over the years. It was about 100 years old and had experienced somewhere between 5 to 10 million fatigue cycles. The owner wanted to know if the structure was safe before investing in a major electrical upgrade.

The study looked at the member forces, AISC fatigue requirements, and non-destructive testing of the eyebars.

The force analysis did not identify any problems. The model results matched the Maxwell diagram in the original drawings. The fatigue analysis indicated stresses in most members below the threshold values in AISC of 4.5 ksi. A few members towards the middle of the truss had stresses near 10 ksi. They had failed at one point, causing the truss to lose over a foot of camber. Up to this point, nothing was of major concern. However, enter non-destructive testing (NDT).

Before any NDT testing occurred, ironworkers stripped the paint of some key joints and discovered cracks, visible to the naked eye, shown in *Figure 8*. The phased array ultrasonic and magnetic particle testing found cracks inside and at the surface of a substantial number of joints. The cracks ranged in size from ⅛ to 2½ inches long and 1⁄64 to 1⁄32 inches wide.

After lengthy discussions and a second engineering opinion, the owner elected to retire the truss – creating a serious operational challenge to the site. Given the size and extent of the cracks and difficulty in repairing eyebars, it was truly the only rational decision.

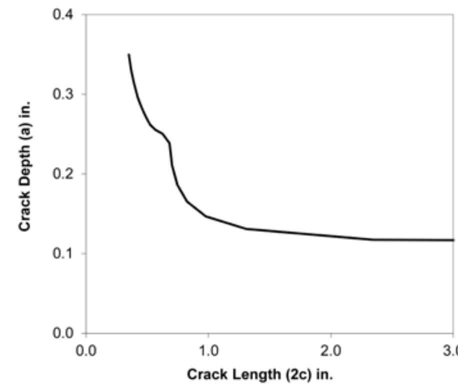

Figure 6. Critical crack size, a break-before-leak condition in the weld.

A key lesson to learn from the bridge crane is the importance of thorough inspection. The stress and fatigue analyses showed the bridge crane was in good shape. However, reality showed a very different picture, one that eventually saved lives.

In the end, the principles of damage tolerance can be applied to traditional civil engineering structures in a way that provides clarity to the cracks they may contain. These are rooted in fracture toughness testing, stress intensity factor solutions, fatigue testing, life correlations, and non-destructive testing. These case studies show the approach in utilizing some of these tools and the insight gained through their application. Greater application of these tools to civil engineering structures would lead to increased safety of the structures for which engineers are responsible.▪

Figure 7. Bridge crane with eyebar bottom chord and diagonal members.

Figure 8. Eyebar cracking.