# Recent Fracture and Fatigue Research in Steel Structures

*By Benjamin V. Fell, Ph.D., P.E. and Amit M. Kanvinde, Ph.D.*

Fracture and fatigue in engineered structures are important phenomena which can have serious consequences if not properly addressed. The Liberty Ship fractures in the 1940s catalyzed the initial development of fracture mechanics, and several events since, including fractures observed during the 1994 Northridge earthquake and recently the I-35 bridge collapse in Minnesota, remind us of the importance of fatigue and fracture. However, design of civil structures still relies largely on force-based analyses with little explicit consideration of fracture, except through prescriptive detailing practices. In the absence of high-fidelity tools to simulate fracture, these detailing practices are often the product of expensive experimentation combined with engineering intuition. While this approach has worked in most situations, the exceptions to this rule are reminders of the necessity of sophisticated fracture simulation techniques.

In this overall context, this article synthesizes recent research by the authors on fracture simulation in structural steel components. This research has been supported by federal, state and private grants, and has resulted not only in fundamental breakthroughs in the science of fracture prediction (especially fracture caused by earthquake-induced Ultra Low Cycle Fatigue), but also in effective strategies to apply these techniques to "real" structural components. Two case studies are presented to evaluate the current state-of-the-art, and to discuss gaps in knowledge. One study involves the simulation of earthquake induced fracture in buckling steel braces in Special Concentrically Braced Frames. The study has direct implications for the detailing of braced frame structures. The other case study is focused on the simulation of fracture in welded components in the presence of several complicating factors. The results are reassuring, suggesting that advanced fracture techniques may be applied successfully to real and complex structural details. Leveraging these tools in an effective way will require active and serious collaboration between academia and the engineering practice.

## Background

Fracture-related structural failures have been considered a critical limit state ever since metals and their alloys were first introduced as construction materials. During the 20th century, the hull fractures of the liberty ship fleet during WWII brought fracture to the forefront of the scientific and engineering awareness. The failures observed in these ships spawned research in what we now know as fracture mechanics, which predicts the behavior of cracked bodies under load.

The main premise of "traditional" fracture mechanics is that cracked bodies fail when the loading produces a stress condition (or a toughness demand) that is in excess of the material toughness capacity. Typically, this material toughness is quantified in terms of a stress intensity parameter (similar to a stress concentration factor) – such as the stress intensity factor $K_c$ (Anderson, 1995). This parameter is calibrated through standard testing procedures and is dependent on the experimental geometry and loading conditions. Therefore, while the stress intensity factor is indicative of material toughness (i.e., glass has a smaller $K_c$ as compared to steel), it does not directly correspond to the physics of crack growth. This is an important distinction from the research presented in this article, which describes a somewhat more fundamental approach to predict fracture.

Over the last five decades, traditional fracture mechanics has proven itself to be a powerful tool for predicting fracture in mechanical and aerospace components. However, several events (*including the 1994 Northridge Earthquake; see next section*) have raised questions about the applicability of traditional fracture mechanics in civil structures, where the conditions leading to fracture are quite different as compared to mechanical components. These persistent questions have necessitated the formulation of new approaches that explicitly simulate micromechanical material processes which are responsible for fracture in civil structures. Fueled by the advances in computing technology, these new approaches can now be applied to full-scale structural components with implications for the fracture resistant design of steel structures.

## What Makes Earthquake-Induced Fracture Different?

The 1994 Northridge and Kobe earthquakes brought fracture to the forefront of civil engineering design issues. Unlike High Cycle Fatigue (HCF), which has long been observed in bridges, these earthquakes revealed a new type of fracture in steel structures – one where traditional fracture and fatigue mechanics are inadequate, barring a few exceptions (Chi, 2000). The limitations of traditional fracture mechanics for earthquake-induced fracture can be traced to two key issues. First, unlike components in aeronautical applications or machines, modern earthquake-resistant structures rely on the dissipation of seismic energy through large cyclic inelastic deformations. This type of loading produces failure in very few cycles (approximately 10 to 15 cycles, as compared to millions for HCF) with extremely large amplitudes (several times the yield strain). The fracture mechanisms that operate in this loading regime (termed Ultra Low Cycle Fatigue, or ULCF) are quite different as compared to the better understood HCF mechanisms. Second, in these situations, the toughness parameter determined from traditional fracture mechanics (e.g. $K_c$) is not uniquely related to the stress/strain state which ultimately governs fracture. Thus, as we move from HCF or brittle fracture to earthquake-induced ULCF, traditional fracture mechanics becomes increasingly difficult to apply with confidence. Research conducted over the past ten years has resulted in novel methodologies to explain these mechanisms.

## Fundamental Research in Earthquake-Induced Fracture

While previous research on steel structures subjected to earthquake loading has relied on empirical approaches and engineering intuition to predict ductility, the research described in this article is more fundamental in nature. The models described here simulate behavior at the material grain scale which has been shown to govern ductile fracture mechanisms.

During the late 60s, McClintock (1968) and Rice and Tracey (1969) developed expressions for the growth of a single void in an elastic-perfectly-plastic continuum as a function of evolving stresses and strains at a continuum point. While the derivation is long and complex, their work led to a criterion (i.e., demand ≥ capacity) which can be used to assess the likelihood of fracture –

$$f(\sigma, \varepsilon^p) \geq \eta \qquad \textit{Equation (1)}$$

In *Equation (1)*, a function of the stress, $\sigma$, and plastic strain, $\varepsilon^p$, states characterizes the demand at any point in a loaded steel structure. On the capacity side, the fracture parameter $\eta$ is similar to the previously discussed $K_c$ and quantifies the toughness, or ductility, of the steel. However, unlike traditional fracture mechanics, the calibration of $\eta$ is directly tied to the stress and strain quantities which govern fracture. While this makes the fracture criterion more applicable to earthquake-induced fracture situations, *Equation (1)* is only valid when fracture occurs due to monotonic tension loading.

Just recently, however, Kanvinde and Deierlein (2007) modified the fracture criterion discussed above to account for the ULCF effects which are observed during earthquake-type loading. The appearance of the model,

$$f_{\text{cyclic}}(\sigma, \varepsilon^p) \geq f(D)\eta \qquad \textit{Equation (2)}$$

is very similar to the previous formulation, but uses a modified demand expression of stresses and strains and introduces a damage function, $f(D)$ ($\leq 1$), which degrades the fracture parameter $\eta$. The damage function accounts for the reduction in ductility caused by cyclic loading. By accounting for fracture conditions in modern steel structures during earthquake loading, *Equation (2)* represents a fundamental advancement in the fracture modeling landscape. While more details of these expressions are presented in the technical literature (Kanvinde and Deierlein, 2007), the important aspect of these two models is that they are formulated at the continuum level such that the stress and strain histories from finite-element analyses govern the fracture prediction instance. Thus, the model depends on the accurate simulation of stress and strain histories at the critical point where fracture occurs.

Through various private (American Institute of Steel Construction) and federal (National Science Foundation) funding agencies, these novel fracture models have been applied to assess fracture ductility in large-scale structural details. Two of these investigations are briefly discussed in the following sections.

## Bridging the Scale Gap

The fracture models discussed in the previous section have several practical implications in the structural and earthquake engineering communities. First, accurate fracture models move researchers more towards simulation-based investigations, thereby decreasing the need for costly large-scale testing. Moreover, it is often difficult to examine performance across a wide-range of experimental variables due to impractical testing situations, high costs, and limited laboratory resources. Thus, using computer simulations allows for parametric studies which can examine situations which may not be feasible to test. Second, the models provide researchers with a tool to develop insights into localized effects which may trigger fracture, such as varying cross-section geometries or fracture toughness properties. However, the application of these models to full-scale structures necessitates a multi-scale modeling approach where behavior at the micromechanical scale is used to predict the performance of large-scale structural details. This leads to several calibration and simulation challenges (discussed more in Kanvinde and Deierlein, 2007 and Fell, 2008).

*continued on next page*

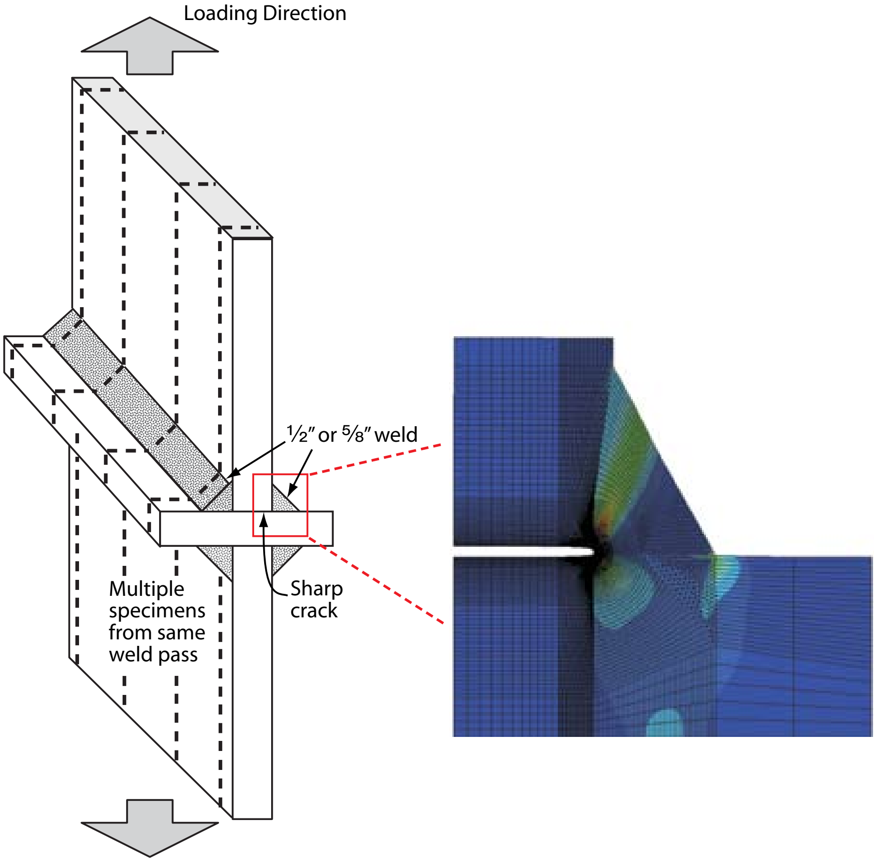

*Figure 1: Schematic of fillet welded connection and corresponding finite-element simulation.*

Since this is an ongoing effort, some of these issues remain unresolved while others have been addressed in recent studies. Two applications of these micromechanical fracture models illustrate several advantages of a simulation-based investigation. In the first, the model is used to predict fracture in welded connections which are copious in structural engineering details. The second evaluates the cyclic fracture model in the context of earthquake-induced fracture of large-scale bracing components. The braces examined here are common to members used in Special Concentrically Braced Frames (SCBFs).

## Ductility of Fillet Weld Connections

While fillet welds are wide-spread in civil construction, expensive pre-qualification testing is still required to quantify the performance of welded connection details. Owing to the complex nature of simulating the various effects which influence the performance of welded connections, such as material heterogeneity and residual stresses, these details are rarely modeled at the full-scale. Perhaps more importantly is the fact that welded connections have become increasingly ductile over the years with new toughness-rated materials and improved workmanship. Thus, as discussed previously, the extensive yielding tends to invalidate traditional fracture mechanics approaches (i.e., using $K_c$). *Figure 1* illustrates a cruciform fillet-welded connection representative of a detail which could be observed in a Partial Joint Penetration (PJP) weld where a sharp crack is introduced by the joining of two plates. Intuitively, a longer crack should decrease the ductility of the connection due to larger stress intensities at the crack tip. However, fracture predictions using the criterion from *Equation (1)* applied to finite element simulations of varying weld and plate sizes shows relatively constant ductility across a wide-range (1¼ to 5 inches) of root notch lengths. In fact, these results were confirmed through twenty-four experimental specimens, demonstrating the capability of the fracture model to simulate localized behavior across a range of geometries. The observation that root notch length does not affect connection ductility is especially reassuring for PJP welds where the un-fused regions create a sharp crack. It seems that if sufficient weld ductility is provided (for example, ensuring toughness rated material such as E70TZ-K2, Grade 480), PJP connections may not be as flawed as once thought for seismic details. These results may impact modern detailing practices in regions of high seismic hazard. The reader is referred to Kanvinde et al (2008-in press) and Myers et al (2008-in press) for a more complete discussion of welded cruciform connections and large-scale PJP connection experiments, respectively.

## Earthquake Performance of Braced-Frame Systems

Special Concentrically Braced Frames (SCBFs) have become increasingly popular lateral load resisting systems in regions of high seismic hazard due to their perceived superior ductility over moment frames. However, recent large-scale tests have suggested that these systems are also prone to fracture at, or before, design level earthquake demands. For this discussion, only brace fracture, driven by a combination of global and local buckling phenomena, will be considered. Due to the extensive yielding in these members during cyclic loading, these types of fractures serve as a practical case study for the cyclic fracture model in *Equation (2)*. Illustrated in *Figure 2* is a finite element simulation of a steel Pipe bracing member (with representative end gusset plates) during earthquake-type cyclic loading, where plastic strain contours indicate the probable location of fracture initiation. Through large-scale finite element models, a parametric study is used to investigate the cyclic ductility of square and rectangular Hollow Structural Steel (HSS) bracing members with varying width-thickness (or b/t) and global slenderness (KL/r) ratios. Using the fracture model in *Equation (2)*, the study shows that for increasing cross-section width-thickness and decreasing slenderness ratios, the maximum axial displacement prior to fracture tends to decrease. While this result is expected due to the increased local buckling susceptibility of non-compact cross sections and stocky braces, the parametric study allows for a variety of combinations between cross-section and brace dimensions to be studied. These results provide quantitative data which can inform earthquake design provisions (such as the AISC Seismic Provisions) as to the influence of various parameters on brace ductility. Specifically, the maximum b/t seismic limits on HSS and Pipe cross-sections may need to revised, or at least verified, through a rigorous simulation study. The reader is referred to Fell et al (2006) and Fell (2008) for a more complete discussion of brace fracture issues.

## Unresolved Issues and the Road Ahead

The two case studies presented in the previous sections represent important advances in the large-scale fracture modeling landscape. While not discussed in this article (see the online version for a list of specific references), these investigations have also raised several questions pertaining to the overall fracture prediction methodology. For example, material heterogeneity from welding processes and uncertainty in the fracture models may substantially influence the simulation results in some cases. Furthermore, the stress state at the critical location of fracture may activate alternative mechanisms which the models in Equations (1) and (2) can not account for. Thus, on-going studies address these various concerns.

In addition to these academic issues, the larger challenge may be assimilating the state-of-the-art into the mainstream of the structural and civil engineering professions, wherein researchers and engineers become more comfortable with simulation-based methodologies rather than expensive tests for performance assessment. Encouraged by the increasing emphasis on Performance Based Earthquake Engineering (PBEE), indications are that this is happening. However, employing these new methodologies as a means to inform design codes will require continued collaboration between academia and industry.▪

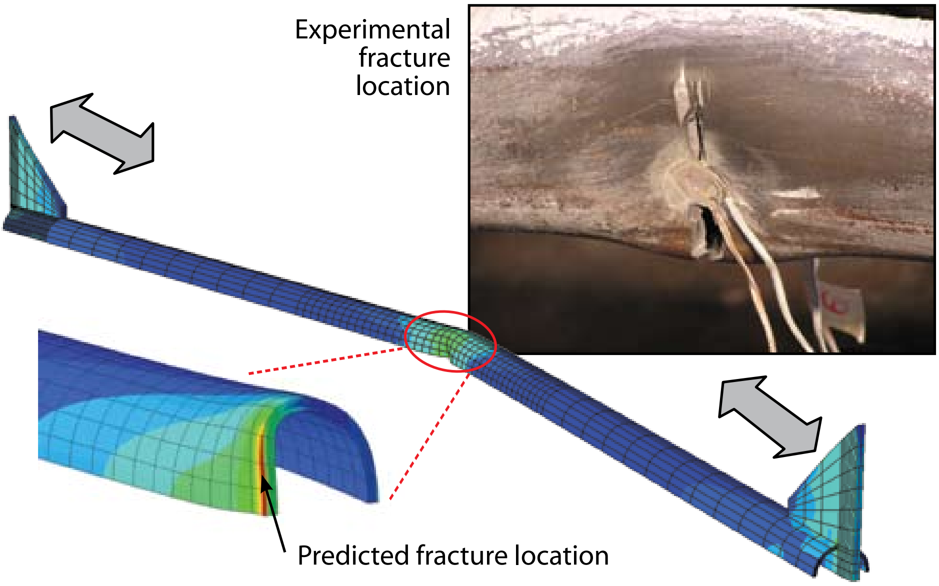

*Figure 2: Fracture of Pipe bracing member during earthquake-type loading.*

*Benjamin V. Fell, Ph.D., P.E. is an assistant professor of structural engineering at California State University, Sacramento. He can be reached at **fellb@ecs.csus.edu**.*

*Amit M. Kanvinde, Ph.D. is an assistant professor of structural engineering at the University of California, Davis. He can be reached at **kanvinde@ucdavis.edu**.*

*Both are active researchers in the area of fatigue and fracture in steel structures.*

## References

American Institute of Steel Construction (AISC). (2005). *Seismic provisions for structural steel buildings*, Chicago, IL.

Anderson, T.L. (1995). *Fracture mechanics*, 2nd Ed., CRC Press, Boca Raton, FL.

Chi, W-M., and Deierlein, G.G. (2000). "Prediction of steel connection failure using computational fracture mechanics." Blume Center TR136, Stanford University, Stanford, CA.

Fell, B.V., Kanvinde, A.M., Deierlein, G.G., Myers, A.M., and Fu, X. (2006). "Buckling and fracture of concentric braces under inelastic cyclic loading." SteelTIPS, *Technical Information and Product Service, Structural Steel Educational Council*. Moraga, CA.

Fell, B.V. (2008). "Large-scale testing and simulation of earthquake-induced ultra-low cycle fatigue in bracing members subjected to cyclic inelastic buckling." Ph.D. Thesis, University of California, Davis, 2008.

Kanvinde A.M. and Deierlein, G.G. (2007). "A cyclic void growth model to assess ductile fracture in structural steels due to ultra low cycle fatigue." *Journal of Engineering Mechanics*, ASCE, 133(6), 701-712.

Kanvinde A.M., Gomez I.R., Roberts M., Fell B.V. and Grondin, G.Y. (2008 - in press). "Strength and ductility of fillet welds with transverse root notch." *Journal of Constructional Steel Research*, Elsevier.

McClintock, F.A. (1968)."A criterion for ductile fracture by the growth of holes." Proc. ASME Meeting APM-14, American Society of Mechanical Engineers, June 12-14, 1968.

Myers, A.T., Kanvinde, A.M., Deierlein, G.G. and Fell, B.V. (2008 - in press). "Effect of weld details on the ductility of steel column baseplate connections." Journal of Constructional Steel Research, Elsevier.

Rice, J. R., and Tracey, D.M. (1969). "On the ductile enlargement of voids in triaxial stress fields." *Journal of the Mechanics and Physics of Solids*, 17, 201-217.