LOCAL CYCLIC VOID GROWTH CRITERIA FOR DUCTILE FRACTURE INITIATION IN STEEL STRUCTURES UNDER LARGE-SCALE PLASTICITY

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INTRODUCTION
Fracture is often the controlling limit state in steel structures, sometimes with catastrophic consequences. As evidenced by recent structural failures, such as the I-35 bridge collapse in Minnesota, in the United States, and the fractures in steel connections during the 1994 Northridge (USA) and 1995 Kobe (Japan) earthquakes, fracture occurs in connections or regions of geometrical discontinuities and material heterogeneities, such as welds. Fracture and fatigue mechanics are highly developed sciences, with widespread application in the mechanical, aerospace and automobile industries. However, traditional fracture and fatigue mechanics are ill-suited for direct application in the context of steel structures in civil construction, for two reasons. First, traditional fracture mechanics is well-suited for characterizing fracture ahead of a sharp crack tip, where only minimal yielding is present. Typically, fracture in civil structures initiates ahead of a blunt stress raiser, and in the presence of large scale yielding. Thus, more fundamental, micromechanics-based approaches must be developed or adapted for characterizing fracture in these conditions. Second, fatigue-induced fracture in civil structures often occurs under seismic loading. Unlike high-cycle fatigue experienced by bridges under vehicular loads (which involves millions of cycles of low stress amplitude), seismic fatigue in structures typically involves five to twenty cycles of extraordinarily large amplitude (on the order of several times the yield strain). Termed Ultra Low Cycle Fatigue (or ULCF), this type of fatigue is of specific interest to civil/earthquake engineers, and special models must be developed to characterize the mechanisms (e.g. microvoid growth and collapse) that control this type of fatigue.

This paper presents research conducted by the authors over the last decade that has focused on developing and applying fracture and fatigue models in the context of the issues discussed above. Two models are described here. One model, applicable to ductile fracture, termed the Void Growth Model (or the VGM) is an adaptation of Rice and Tracey’s [1] derivation for the growth of microvoids. The second model, more applicable to ULCF, is termed the Cyclic Void Growth Model (CVGM), Kanvinde and Deierlein [2]. As suggested by its name, the model is an extension of the VGM such that it accounts for the cyclic effects of microvoid collapse and deterioration. Consequently, it can characterize fracture under seismic conditions. Research by the authors has focused on several aspects of these models, including (1) fundamental model development (2) development of methods for calibration (3) development of a probabilistic, maximum-likelihood-based framework for the application of these models and (4) validation of the models using coupon, component and large scale experiments. The paper discusses these various components of this research, within the overall context of structural safety evaluation through advanced simulation. Using this research as an example, the main objective of this paper is to provide a comprehensive view of the current state of the art in fracture modeling of steel structures. The paper begins by providing an overview of the models themselves, before discussing their calibration, validation and the statistical framework.
1  MICROMECHANICS-BASED MODELS FOR FRACTURE AND ULCF

1.1  Micromechanisms of ductile fracture and ultra low cycle fatigue

Mild steel, commonly used in civil construction, typically exhibits ductile fracture accompanied by large scale plasticity. Under monotonic loading, fracture occurs when microvoids initiating at sulphide or carbide inclusions grow under the plastic strains, leading to microvoid coalescence. Initially, the voids grow independent of one another, but upon further growth, neighboring voids interact and eventually, plastic strain is concentrated along a certain plane of voids. At this point local necking instabilities cause the voids to grow suddenly forming the macroscopic fracture surface. Fig. 1 illustrates the micromechanism of ductile fracture schematically, whereas Fig. 2 shows a scanning electron micrograph of a surface that has fractured due to void growth and coalescence. The dimples on the surface show the locations of the voids that have coalesced. Under cyclic loading (i.e. ULCF), the void growth is accompanied by void collapse and deterioration of the material matrix surrounding the voids. Figs. 3 and 4 are similar to Figs. 1 and 2, illustrating the micromechanism and the micrographs for ULCF. The micrographs shown in Figs. 2 and 4 are obtained for the same steel material, albeit subjected to monotonic and cyclic loading. The shallower dimple size (indicating material deterioration) is evident in Fig. 4.

![Void nucleation](image1)
![Void growth](image2)
![Unstable Necking](image3)
![Void coalescence](image4)

**Fig. 1.** Micromechanism of ductile fracture

![Fractograph of ductile fracture](image5)

**Fig. 2.** Fractograph of ductile fracture

![Void growth](image6)
![Void collapse](image7)
![Material damage](image8)
![Fracture](image9)

**Fig. 3.** Micromechanism of ULCF

![Fractograph of ULCF surface](image10)

**Fig. 4.** Fractograph of ULCF surface
1.2 The Void Growth Model and the Cyclic Void Growth Model

As discussed above, the processes of void nucleation, growth and coalescence are responsible for ductile fracture initiation under monotonic loading. Previous research, by Rice and Tracey [1] has shown that void growth is controlled by the equivalent plastic strain shown that void growth is controlled by the equivalent plastic strain, $\varepsilon_p$, and stress triaxiality $T = \sigma_m/\sigma_e$, where $\sigma_m$ is the mean or hydrostatic stress and $\sigma_e$ is the von Mises stress. Equation (1) describes the critical condition of the Void Growth Model. The “void growth demand” is expressed in the numerator in the Equation, which is based on derivations by Rice and Tracey. This quantifies a void growth that must exceed the void growth capacity to trigger ductile fracture. As shown in the equation, the void growth demand is based on stress and strain evolutions at a continuum point, and can be determined through detailed FEM analysis. The void growth capacity is characterized by the material parameter $VGI_{\text{critical}}^{\text{monotonic}}$, which can be calibrated from tests on circumferentially notched tensile (CNT) specimens (see Fig. 5). Typically, these calibrations require the use of finite element simulations complementary to the CNT tests. However, recent work by the authors (Myers et al. [3]) provides methods for calibrating the material parameter of the VGM directly through test data. Once the material parameter has been calibrated, fracture in a structural component may be predicted to occur when the Fracture Index defined in Equation (1) exceeds unity, i.e. when the void growth demand exceeds the void growth capacity at that material point –

$$\text{Fracture Index} = \frac{\int_0^\varepsilon \exp (1.5T) \, d\varepsilon_p}{VGI_{\text{critical}}^{\text{monotonic}}} > 1$$

While originally proposed for steels used in pressure vessels and nuclear applications, extensive studies by the Kanvinde and Deierlein [4] have demonstrated the accuracy of the VGM for a large variety of low-carbon structural steels used commonly in civil engineering construction. Referring to Fig. 3, ULCF involves both void growth and collapse, due to the reversed cyclic nature of the loading. To address this issue, the authors conducted a comprehensive analytical and experimental study, that resulted in the development of the Cyclic Void Growth Model - CVGM (Kanvinde and Deierlein [2]) that simulates the micromechanisms of void growth, collapse and cyclic degradation that are responsible for Ultra Low Cycle Fatigue. Equation (2) describes the critical condition of the CVGM that must be attained to trigger ULCF initiation. Equation (2) is similar to (1), such that the numerator of the equation reflects the cyclic micromechanical void growth demand and is based on strains and stresses inferred through finite element analysis, and the denominator reflects material capacity, calibrated through small scale tests. ULCF is assumed to initiate when the Fracture Index (FI) exceeds 1. In comparison to the VGM, the CVGM contains one additional parameter $\lambda$ (quantifying the rate of capacity degradation) that is calibrated through multiple cyclic tests of notched bar specimens.

$$\text{Fracture Index} = \frac{\sum \int_{tensile\text{-cycles } \varepsilon_t} \exp(1.5T) d\varepsilon_p - \sum \int_{compressive\text{-cycles } \varepsilon_c} \exp(1.5T) d\varepsilon_p}{VGI_{\text{critical}}^{\text{monotonic}} \exp(-\lambda \varepsilon_{\text{accumulated}})} > 1$$

Similar to the VGM, the CVGM model too, has been validated using fractographic studies and coupon scale tests that suggest the likely micromechanism to be void growth and collapse. The next section outlines the calibration of the VGM, and a probabilistic framework within which the VGM and CVGM may be calibrated and applied to full-scale structural components. A subsequent section discusses the validation of this framework through large-scale tests.
2 DEVELOPMENT OF METHODS FOR THE CALIBRATION FOR THE MODELS

2.1 A FEM-Free method for the calibration of the VGM

The method typically used to calibrate models such as the VGM is based on conducting finite element simulations that complement the calibration coupons (such as the CNT coupons – See Fig. 5). The deformation at which the test specimen fractures is imposed on the FE models, and the stress and strain quantities, as recovered from that simulation at the instant of fracture are substituted into Equation (1), to back calculate \( VGI_{\text{monotonic}}^{\text{critical}} \). Thus, the material toughness parameter \( VGI_{\text{monotonic}}^{\text{critical}} \) for the VGM depends on stress and strain quantities that are the product of highly non-linear and inelastic specimen response. The use of complementary FEM adds significant expense and inconvenience to the calibration process for the toughness parameter. To address this issue, recent research by the authors (Myers et al [3]) has developed relationships to directly infer the stress and strain states at fracture from experimental data (without finite element simulation) resulting in an approach to calculate the material toughness \( VGI_{\text{monotonic}}^{\text{critical}} \) directly from the initial CNT geometry, material properties, and the measured deformation at fracture. These relationships are based on the results of exhaustive finite element simulations. In essence, they are similar to those used in fracture mechanics standards (e.g. ASTM E 399, [5]), wherein the stress intensity factor for fracture specimens (such as the compact tension specimen) is expressed as a function of the load and geometrical properties (e.g. \( a/W \) – the crack length to specimen width ratio) through nonlinear regression models. The VGM model uses the equivalent plastic strain \( \varepsilon_p^p \), and the stress triaxiality \( T \). Based on the research discussed above, Equations (3) and (4) below express test-only based estimates of these quantities denoted as \( \varepsilon_{\text{method}}^p \) and \( T_{\text{method}} \):

\[
T_{\text{method}} = (1/3 + \ln(D_{NR} / 4R_N + 1) \cdot (1.14 - 2.48 \cdot \ln(D_{NR} \cdot n / R_N)))
\]  

(3)

\[
\varepsilon_{\text{method}}^p = 2 \ln(D_{NR} / D_{NR,post-fracture}) \cdot (0.822 - 0.182 \cdot \ln(D_{NR} \cdot n / R_N))
\]  

(4)

In the above equations, \( n \) is a material hardening coefficient of the Ramberg-Osgood hardening relationship, refer [3], whereas all the other terms represent geometrical aspects of the test specimens (refer Fig. 5). The fracture deformation is expressed in terms of the necked diameter of the notch measured after fracture – see Fig. 6.

\( D_{NR}, \) Notch Root Diameter  \hspace{1cm} \( R_N, \) Notch Radius

\( D_{UN}, \) Unnotched Diameter

\( D_{NR,post-fracture}, \) Fracture Surface

\( D_{NR}, D_{NR,post-fracture} \)

**Fig. 5.** Schematic of circumferentially notched tension (CNT) coupon  \hspace{1cm}  **Fig. 6.** Post-fracture notch root diameter of a CNT

Once the parameters have been calibrated in this way, they may be used for predicting fracture through finite elements simulations of full scale structural components.
2.2 A Maximum likelihood based framework for the calibration of the CVGM

The methodology underlying the calibration of the CVGM is similar to the VGM, wherein the critical stresses and strains corresponding to the instant of fracture (as obtained from experimental data from CNT specimens) are determined through FEM, and then substituted into Equation (2) to back-calculate the material parameters. However, there are two key differences between the VGM and the CVGM. First, the CVGM contains an additional parameter $\lambda$, that characterizes the rate of deterioration of the material matrix with respect to the damage index (the accumulated plastic strain) – Refer Equation (2). Moreover, high amplitude cyclic loading with a small number of random cycles (such as encountered during earthquake-type ULCF, and applied to the CNT specimens) raises another important question. Although the final cycle of the experiment corresponds to fracture, the preceding cycles contain information about material response too, since they indicate non-failures, which represent lower bounds on material toughness. Sometimes, due to the irregular nature of the loading history, some of these preceding cycles may load the specimen to a point, which, after calibration of the material may represent a point at which the fracture index (refer Equation 2) is greater than 1.0, implying that the specimen should have failed on this preceding cycle, whereas it did not. To reconcile this dichotomous situation, research by the authors (Myers et al, [3]) proposes a framework within which, the non-failure cycles can be integrated into the calibration process in a systematic way. The basis for this method is to assume a distribution of the material parameters that maximizes the likelihood of the experimental data being observed, by incorporating the non-failure cycles by assuming them as lower bounds on material toughness. To illustrate this process, consider a calibration experiment in which failure occurs on the second tensile excursion. To apply the maximum likelihood framework, a distribution of the material parameters $VGI_{\text{critical}}^{\text{monotonic}}$ and $\lambda$ is assumed. This implies an assumption of their mean values as well as standard deviations, and a statistical distribution (e.g. Gaussian) resulting in a total of four parameters to calibrate the model in a probabilistic way. Once this is done, the fracture index may be evaluated in the FE simulation at two points (1) at the point of load reversal in the first, non-failure cycle and (2) at the point of failure during the second cycle. Given the assumed parameters, the likelihood of observing the test data may be calculated based on Equation (2) for the CVGM and the assumed statistical distributions. For example, at the first load reversal, since failure has not occurred, the fracture index implied by Equation (2) is less than unity. If the stress and strain history at this point is known, through FE simulations, then the critical strains may be substituted into Equation (2) to calculate the probability (likelihood) of this region, i.e. $F_i < 1.0$, in the space of the material parameters whose distributions are assumed a priori. For the second cycle, the fracture index exactly equals unity, and thus the likelihood of fracture may be determined based on the assumed probability distribution functions of the material parameters. A product of these likelihoods represents the overall likelihood of observing the test response, given the parameters. The parameter set that maximizes the likelihood over various tests is calibrated as the appropriate one. Myers [3] describes the process and its application in greater detail. The subsequent section describes the validation of the fracture modeling approach discussed in this paper through the application to large scale component tests.

3 VALIDATION OF THE FRACTURE MODELING APPROACH

Several large scale experiments were conducted by the authors for the purpose of validating the methodology outlined in this paper. These include nineteen experiments on hollow steel braces subjected to cyclic inelastic buckling (Fell et al. [6]). In these situations, fracture is controlled by the amplification of strains due to local buckling of the cross section. In addition to the experiments on braces, six experiments were conducted on column base connections (Myers et al [3]), subjected to cyclic deformations as would be expected in an earthquake. These tests were designed to interrogate the failure mode of weld-fracture, at the weld detail between the column and the base plate. Fig. 7 shows a photograph and complementary simulation from the brace tests, whereas Fig. 8 shows a similar graphic from the column base plate tests.
Andy, what would be ideal here is a graphic showing the overall test setup, and a small inset of the FEM, e.g. Fig 6.4b of your thesis, with contours, if possible.

Here, one could show an appropriate graph between Figure 6.13-6.17, with only one CDF to illustrate the process, i.e. remove the other two CDFs for the different lambda values.

**Fig. 7 – Column base connection test and simulation**

**Fig. 8. Probabilistic prediction of fracture initiation in the test**

Referring to Figs. 7 and 8, various aspects of this methodology (i.e. model development, calibration, and the probabilistic framework) may be used to predict failure in structural components in a systematic way. While several aspects of this methodology require refinement as discussed in the next section, the process offers several advantages over traditional, experiment-based methods, i.e. (1) it is inexpensive, compared to large scale experimental testing (2) it is based on the fundamental processes that are responsible for fracture, and thus it may be generalized more conveniently to alternate geometries, materials and loading histories, and (3) it incorporates material randomness in a systematic way, such that reliability of existing and future structures may be quantified in a rigorous manner.

4 SUMMARY AND ACKNOWLEDGMENT

This paper summarizes research conducted by the authors over the last decade, that has been focused on predicting fracture and earthquake induced fatigue in civil structures. This research includes experiments encompassing several scales (coupon scale to component scale), high-fidelity continuum finite element simulations, fractographic studies, and probabilistic analysis. The result is a comprehensive methodology that may be applied with confidence for characterizing fracture-fatigue limit states in steel structures. However, several aspects of this methodology require additional work. For example, fracture under low stress triaxiality (that occurs on corners of structures) is not well understood. Similarly, the effect of spatial randomness in material fracture toughness on the resilience of large components has not been characterized. Ongoing work by the authors addresses these issues. The authors are grateful to the National Science Foundation of the USA (Grant # CMMI 042192), which provided major funding for these studies. Support of the staff at the NEES-Berkeley laboratory is greatly appreciated as is the assistance of various undergraduate and graduate student researchers at Stanford University and the University of California at Davis.

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