

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 2, February 2018

Predicting Fracture in Steel Structures

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ABSTRACT: Fracture is an extreme limit state in steel structures, often precipitating structural failure or serious loss of function. Methods to predict fracture in civil structures include traditional approaches developed in other disciplines (mechanical or aerospace engineering) subsequently adopted in structural engineering, as well as approaches to characterize earthquake-induced fractures originating within civil engineering. Developed over nearly six decades, the state of the art is composed of theories and models that address fracture over multiple scales and are targeted toward disparate application scenarios. The report examines these approaches from a structural engineering standpoint, considering trade-offs in accuracy and expense, while identifying areas for improvement. Traditional approaches (including linear elastic and elastic plastic fracture mechanics) are presented, followed by newer local approaches that are better suited for scenarios where traditional approaches are inapplicable. By simulating micro mechanisms such as micro void growth as well as granular cleavage, local approaches address fracture under large-scale yielding, ultralow-cycle fatigue (which occurs during earthquakes), and low-stress triaxiality, all of which are important in civil structures. The physical basis for these approaches is outlined, with a summary of best practices for calibration and application. However, these local approaches have limitations as well, and often require substantial resources for successful implementation. With this background, optimal fracture assessment strategies are outlined for common structural scenarios, considering accuracy and cost. Limitations of the entire fracture modeling framework are summarized because they pertain to mainstream adoption within structural engineering research and practice. As the profession moves toward accurate performance characterization, it is anticipated that research will accelerate to overcome these limitations.

I. INTRODUCTION

Failure of steel structures triggered by fracture is a much-feared situation across various engineering disciplines. Beginning with the Liberty Ship fractures in the 1940s (Sheldon 2010) that catalyzed the initial development of fracture mechanics as a field of study, catastrophic structural failures are periodic reminders of the consequences of fracture. Prominent examples include the fracture of the Alexander Kielland drilling rig in 1980 (Almar-Naess et al. 1984) resulting in 123 deaths, and steel building fractures during the 1994 Northridge and 1995 Kobe earthquakes. Because some of these earlier fractures occurred outside the realm of civil infrastructure, fracture mechanics initially evolved within the mechanical, aero-space, and nuclear engineering disciplines. Within civil engineering, fracture was largely addressed through prescriptive detailing or through design checks in which applied stresses (calculated through classical strength of materials-type approaches) were checked against empirical stress capacities (American Welding Society 2015). The Northridge and Kobe earthquakes underscored the problems with these empirical approaches, providing impetus for studying fracture within a context specific to civil (especially earthquake) engineering. This resulted in adaptation of existing methodologies to civil engineering (Barsom and Rolfe 1999), as well as the development of new models and methods (Kanvinde and Deierlein 2007) that address problems peculiar to civil (structural) engineering, e.g., earthquake-induced ultralow-cycle fatigue (ULCF). The subsequent evolution of fracture mechanics within structural engineering has been influenced by various factors including (1) its application scenario, e.g., sharp versus blunt cracked components, monotonic versus cyclic loading, and limited versus extensive yielding within the component; (2) computational resources available at the time of its development; and (3) established trade practices and standards for material testing and characterization. Not surprisingly, fracture mechanics sometimes appears to be a patchwork of competing theories and methodologies whose suitability for addressing structural fracture under various conditions is somewhat unclear. In view of this, the primary objective of this report is

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to present fracture prediction approaches from a structural engineering standpoint with consideration of the following factors: (1) application scenario, (2) trade-offs between expense and accuracy, (3) limitations and areas for refinement, and (4) improvements to professional practices to enable more effective fracture simulation.

1.1 Motivation

A general overview of fracture in steel structures, describing the responsible micro mechanisms across multiple scales. The subsequent section outlines methodologies for fracture prediction, recognizing that all ultimately seek to characterize common physical mechanisms, albeit in varying contexts and at different scales, such that these methods are suited for different application scenarios. The next section examines scenarios (materials, loading types, geometry) common to structural engineering and the suitability of the different fracture models to address them.

1.2 Background

The report then summarizes limitations of the state of the art as they pertain to structural engineering, outlining areas for improvement in the modeling methods themselves and in professional practices that are necessary to fully leverage these methods. Finally, noteworthy applications of fracture mechanics are discussed to illustrate its growing acceptance in professional practice. The focus of the report is to review the state of the art for predicting fracture in civil steel structures, and not the state of the art of fracture mechanics itself. This is an important distinction because the former is subject to subjectivities in material characterization owing to trade practices, as well as a relative lack of resources (compared to other disciplines and applications) for effective application of some of the most advanced fracture mechanics approaches. Consequently, the report emphasizes approaches that are practical for structural engineering while discussing the advanced models to provide fuller context.

1.3 Objectives

1. The primary objective of this report is to present fracture prediction approaches from a structural engineering standpoint with consideration of the following factors: (1) application scenario, (2) trade-offs between expense and accuracy, (3) limitations and areas for refinement.
2. The report examines these approaches from a structural engineering standpoint, considering trade-offs in accuracy and expense, while identifying areas for improvement. Traditional approaches (including linear elastic and elastic plastic fracture mechanics) are presented, followed by newer local approaches that are better suited for scenarios where traditional approaches are inapplicable.
3. By simulating micro mechanisms such as micro void growth as well as granular cleavage, local approaches address fracture under large-scale yielding, ultralow-cycle fatigue (which occurs during earthquakes), and low-stress triaxiality, all of which are important in civil structures.
4. The physical basis for these approaches is outlined, with a summary of best practices for calibration and application

1.4 Scope of the Project Work

Fracture is an extreme limit state in steel structures, often precipitating structural failure or serious loss of function. Methods to predict fracture in civil structures include traditional approaches developed in other disciplines (mechanical or aerospace engineering) subsequently adopted in structural engineering, as well as approaches to characterize earthquake-induced fractures originating within civil engineering. Developed over nearly six decades, the state of the art is composed of theories and models that address fracture over multiple scales and are targeted toward disparate application scenarios.

II. LITERATURE REVIEW

1. The fracture performance of steel wires for civil, engineering applications remains a major concern in civil engineering construction and maintenance of wire reinforced structures. The need to employ approaches that simulate micromechanical material processes which characterizes fracture in civil structures has been

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emphasized recently in the literature. However, choosing from the numerous micromechanics-based fracture models, and identifying their applicability and reliability remains an issue that still needs to be addressed in a greater depth. Laboratory tensile testing and finite element tensile testing simulations with the shear, ductile and Gurson-Tvergaard-Needleman's micromechanics based models conducted in this work reveal that the shear fracture model is an appropriate fracture model to predict the fracture performance of steel wires used for civil engineering applications. The need to consider the capability of the micromechanics-based fracture model to predict the "cup and cone" fracture exhibited by the wire in choosing the appropriate fracture model is demonstrated. [1]

2. Current design codes for fire resistance of structures are based on isolated member tests subjected to standard fire conditions. Such tests do not reflect the behaviour of a complete building under either normal temperature or fire conditions. Many aspects of behaviour occur due to the interaction between members and cannot be predicted or observed in tests of isolated elements. Performance of real structures subject to real fires is often much better than that predicted from standard tests due to structural continuity and the provision of alternative load paths. This paper reports on the results of a collaborative research project (Tensile membrane action and robustness of structural steel joints under natural fire, European Community FP5 project HPRI—CV 5535) involving the following institutions: Czech Technical University (Czech Republic), University of Coimbra (Portugal), Slovak Technical University (Slovak Republic) and Building Research Establishment (United Kingdom). It consists of an experimental programme to investigate the global structural behaviour of a compartment on the 8-storey steel–concrete composite frame building at the Cardington laboratory during a BRE large-scale fire test, aimed at the examination of the temperature development within the various structural elements, the corresponding (dynamic) distribution of internal forces and the behaviour of the composite slab, beams, columns and connections. [2]
3. The Northridge and Kobe earthquakes demonstrated that fracture is an important mode of failure in steel moment connections during earthquakes. Investigations conducted since these earthquakes revealed important limitations of traditional fracture mechanics in characterizing ductile crack initiation under large-scale yielding which is more likely in post-Northridge connections with smaller flaws and tougher materials. Micromechanical models that capture the fundamental mechanisms of ductile crack initiation can predict fracture even in situations of widespread yielding. This paper discusses one such model the Stress Modified Critical Strain (SMCS) model, and its applications to realistic connection situations. The paper introduces the model and then describes a series of finite element analyses used to calibrate and apply the model to situations such as bolt-hole and Reduced Beam Section (RBS) type connection tests. It is observed that due to the relatively flat stress-strain contours in these specimens, the SMCS model can be applied using a relatively coarse mesh, indicating that the micromechanical models may be feasible for widespread use in fracture prediction. The SMCS model predicts fracture with good accuracy. The paper then describes the use of the SMCS models to transfer results between experiments, based on two different configurations of the bolt-hole experiments, where the conditions for fracture in either situation are observed to be identical when in fact the loading configuration is different. The paper concludes by referencing a larger study by the author that focused on micromechanical models for predicting low-cycle fatigue in structures during earthquakes. It is briefly noted that the micromechanical models such as the SMCS can be relatively free from assumptions and virtually extended to any loading/stress-situation because they aim to capture the fundamental mechanism of failure. [3]
4. This paper presents a simple criterion to predict the failure of steel structures due to the interaction effect of fracture and fatigue which is termed as extremely-low cycle fatigue (ELCF) failure. The criterion has been obtained from further simplification of available cyclic void growth model (CVGM). Initially the simplified ELCF fracture criterion is clearly presented and associated ELCF fracture prediction methodology is also indicated. The simplified criterion is then employed to determine ELCF fracture of some structural models. Hence verification of the simplified criterion is confirmed by comparing the results with previous criterion

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based estimations. Then the simplified criterion is applied to predict the ELCF fracture of a reduced beam section specimen. Finally, study tends to conclude that the simplified criterion produces reasonable accurate prediction to ELCF fracture of steel structures where magnitude of triaxiality remains relatively constant. [4]

5. The crack spacing of reinforced concrete structures has a major influence on structural performance. The fracture energy criterion of crack formation was employed to predict the crack spacing of concrete based on the linear elastic fracture mechanics. This method employs analytical derivation of three dimensional axisymmetric elastic mechanics problems. The simplified solution for a direct tension specimen with a single rebar at the center is derived and both the fracture mechanics criterion as well as the strength criterion is put forward to predict the crack spacing of reinforced concrete members. The influence of concrete strength to the crack spacing is also well explained by this method. Data analysis of classical test results implies a proof for employing fracture mechanics criterion instead of the strength criterion. [5]
6. Steel bridges play an important role in the transportation system of many countries. To ensure that bridges are structurally sound, engineers monitor their performance, which is known as structural health monitoring. Historical evidence indicates that bridge damage is pervasive and that the service life of bridges is decreasing. To manage safety and costs, engineers must be able to accurately predict the service life of bridges. A statistical method to predict service life for steel bridges is presented, which can assist bridge engineers, bridge owners, and state officials in the objective assessment of deteriorated bridges for retrofit or replacement. Timely repair and retrofit of bridges increase their safety levels and decrease costs. A nonparametric statistical approach based on the bootstrap method for stress analysis for fatigue life prediction of steel bridge components is proposed. The bootstrap provides a simple approach for the reproduction of the extremely complex probability distribution of measured strain data. It is completely automated numerical method which requires no theoretical calculations and it is not based on the asymptotic results. The service life index is introduced which quantifies the fatigue life of steel bridges under daily traffic loads. A regression model is developed for the prediction of remaining service life of steel bridges using a service life function. The predicted remaining service life derived from the function can contribute to effective management of steel bridges. [6]
7. Fatigue is a localized and progressive process in which structural damage accumulates continuously due to the repetitive application of external loadings such as vehicles for steel bridges, winds for high-rise buildings, waves for offshore platforms, and temperature for turbine engines, while these applied loadings may be well below the structural resistance capacity. This kind of process is extraordinarily dangerous because a single application of the load would not create any abnormal effects, whereas a conventional structural stress analysis might lead to a conclusion of safety that does not exist. Over a long period of time, the strength and serviceability modes of failure have been well investigated in the professional engineering communities. However, as one of the most critical forms of damage and principal failure modes for steel structures, fatigue is still less understood in terms of the cause of formation and failure mechanism. It is therefore essential to seek novel methodologies and develop advanced technologies for seizing the fatigue phenomenon and conducting reliable assessment of fatigue damage status of steel bridges which serve as vital components in the transportation infrastructure of a nation. [7]

III. METHODOLOGY

a. Mechanisms and Physics of Fracture in Structural Steel

Referring to the previous section, fracture criteria seek to establish conditions (at the component or continuum scale) under which microstructural fracture mechanisms are activated. This section provides an overview of these mechanisms. When the steel micro-structure (consisting of metal grains along with carbide and sulfide inclusions) is subjected to sufficient stress or strain, material separation occurs through one of two processes or their combination:

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(1) cleavage due to tensile stress rupturing molecular bonds within or at boundaries of grains, and (2) microvoid growth and coalescence due to inelastic flow of material around initiated microvoids, leading to their enlargement and subsequent coalescence to form the fracture surface. Figs. 1(a and b) schematically illustrate these processes, as well as the resultant fracture surfaces. Cleavage fracture does not require significant inelastic dissipation to propagate, whereas microvoid growth and coalescence is accompanied by plastic dissipation. The implication of this at the macrostructural scale is that cleavage often propagates in an unstable manner (with-out increase in applied loads), whereas microvoid controlled fracture, requiring higher energy, propagates slowly and stably with respect to applied loads. As a result, cleavage is often referred to as brittle, whereas tearing is often considered ductile. While true in general, the suddenness of fracture at the macro scale, often perceived as brittleness, is not necessarily associated with cleavage and is controlled by factors such as strain energy stored in the en-tire component, loading rate, and its interaction with the energy required to propagate the crack locally. For example, under high loading rates or load-controlled conditions, even a locally ductile fracture mechanism (microvoid growth) can result in highly non-ductile performance (sudden fracture) at the structural scale.

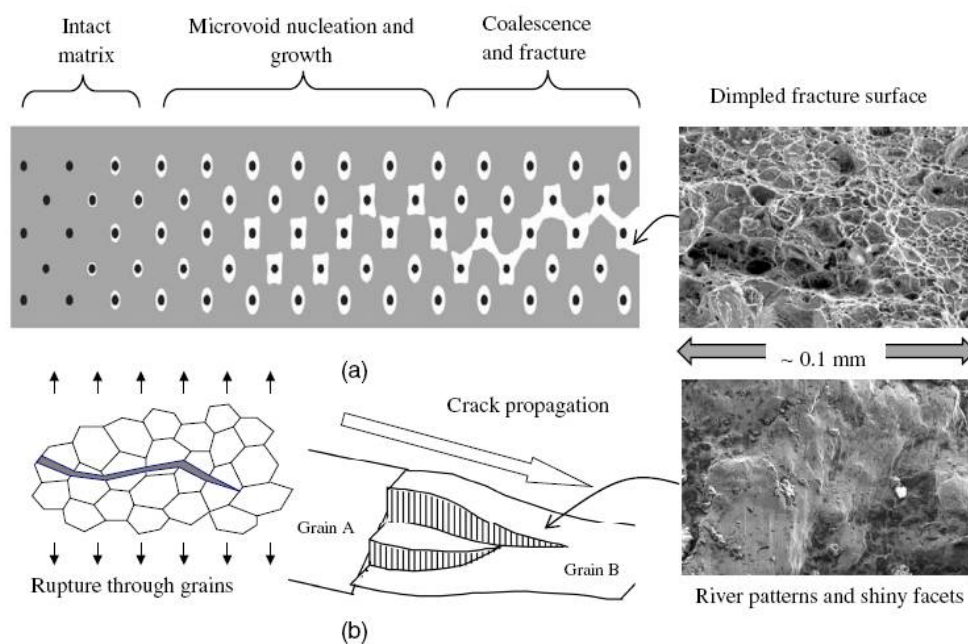


Fig. 1. Micro mechanisms of fracture and corresponding failure surfaces: (a) microvoid growth and coalescence; (b) cleavage; transgranular cleavageshown

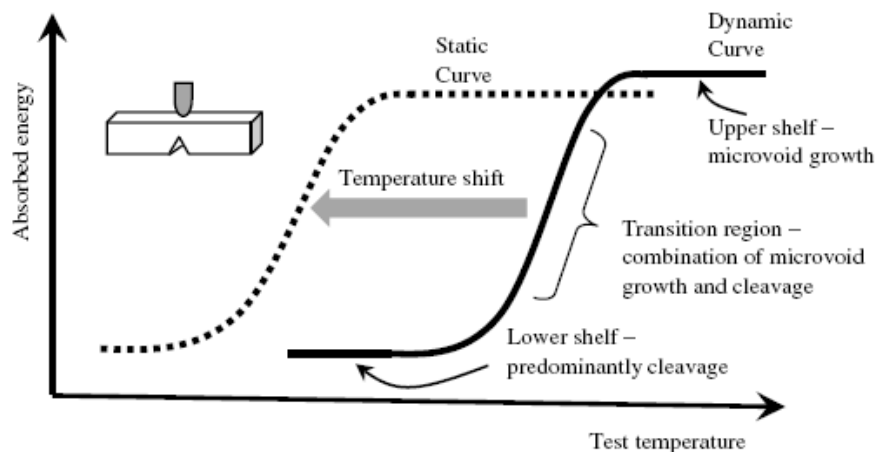


Fig. 2.Characteristic temperature transition response of structuralsteels

It shows a typical CVN curve, plotting the absorbed CVN energy (as a measure of toughness) against temperature. Referring to the figure, three distinct regions are observed. At low temperatures, fracture is controlled by cleavage resulting in low toughness. At intermediate temperatures, a transition region is observed, where some ductile tearing may precede cleavage, resulting in increased toughness. Finally, at higher temperatures an upper shelf is observed, where fracture is controlled entirely by ductile tearing. Fig.2 also shows the effect of loading rate on CVN, such that an increased loading rate lowers toughness, especially in the transition region. With this background, the next section discusses fracture simulation methodologies for steel structures

b. Models for Predicting Fracture in Steel Structures

Empirical methods to characterize fracture (or more generically, structural failure) have been prevalent for several decades and predate the advent of the discipline of fracture mechanics, often considered coincident with the introduction of the Griffith criterion for fracture, based on strain energy release rate. The application of these methods involves calculating a force or deformation demand through structural analysis and then comparing it to a corresponding capacity, determined through (ideally full-scale) component testing. This approach is accurate (assuming the tested components are sufficiently similar in scale and construction to the field prototypes), but expensive and difficult to generalize to dissimilar structure components. Nevertheless, it is used when (1) there is a low tolerance for inaccuracy or modeling uncertainty that may be introduced due to lower-scale methods, and (2) sufficient resources are available for large-scale testing. Successful applications of this approach include the multiuniversity campaign of large-scale testing and analysis during the SAC steel project, motivated by the Northridge moment frame fractures. The design considerations arising from these were based primarily on the experimental observations.

c. Application to Common Structural Engineering Situations

This section examines the suitability of various models (discussed in the previous section) for common structural engineering scenarios. The discussion is premised on the notion that the ultimate objective of fracture modeling is to determine a global (or structural) force or deformation at which fracture (and associated loss of strength) occurs. This may be required for a component that is being designed or is already in service, or sometimes for developing broader insights into effects of detailing or material properties in support of design standards. Referring to prior discussion, different fracture models require disparate resources for simulation as well as material characterization, resulting in varying levels of accuracy for different applications. Following this, the primary objective of this discussion is not to advocate for a particular modeling approach, but rather to provide perspective for optimal modeling strategies, recognizing that the optimal strategy is influenced by available resources for calibration experiments and computational

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resources, as well as the desired accuracy in prediction, noting that a full-scale test of the component is the most accurate but also likely the most expensive approach. The section describes conditions commonly occurring in structural engineering and examines various modeling options for each. Fig. Schematically illustrates structural components where these conditions may be encountered.

Referring to Fig. , the primary classification of the scenarios is whether they include sharp cracks or smooth transitions in geometry. Sub classifications pertain to whether the components are monotonic or cyclic, and whether there is the expectation of large-scale yielding prior to fracture. These are not all possible combinations, primarily because some (e.g., blunt notched conditions with large or small-scale yielding) are essentially equivalent in terms of their amenability to modeling approaches. Before discussing each scenario, it is useful to establish the connotations of sharp crack versus smooth transitions and small- versus large-scale yielding. Components may be classified as sharp cracked if they contain cracks (or flaws) that are introduced without removal of material (sometimes referred to as atomically sharp cracks). Such cracks are typically the result of high cycle fatigue where cracks grow under

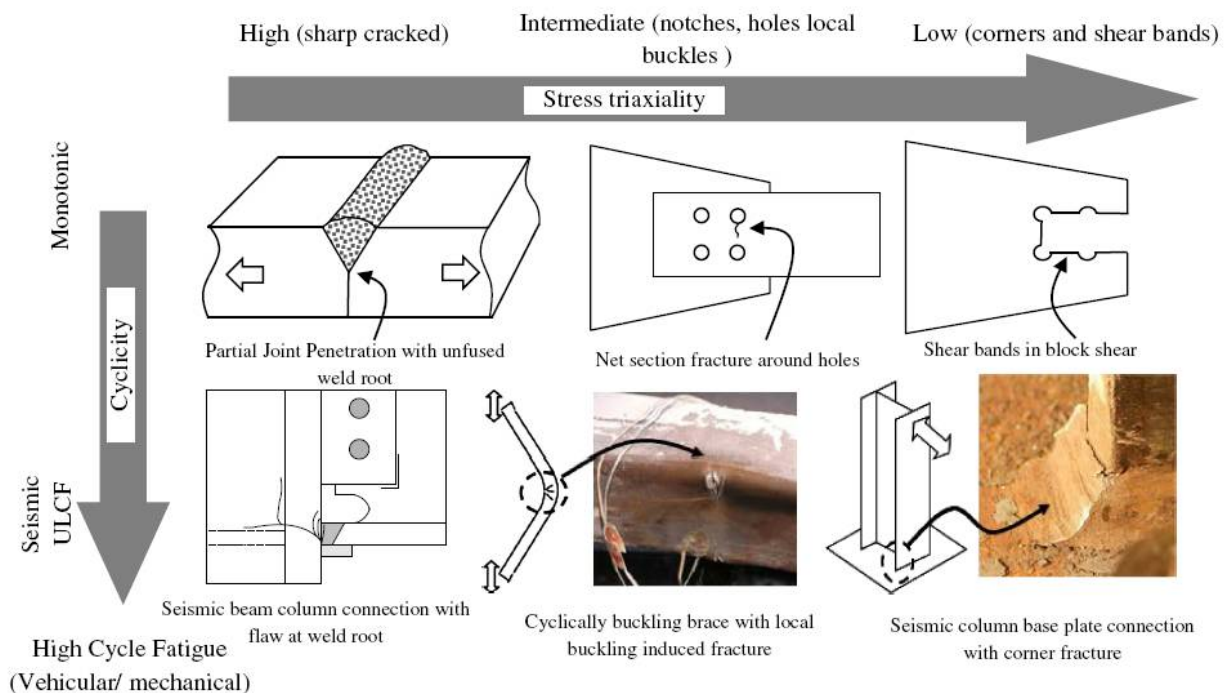


Fig.4. Common structural engineering situations in the space of stress triaxiality and load cyclicality

Cracks in steel bridge decks are a common civil engineering example. Sharp cracks may also be formed when fracture initiates at a blunt notch or in a smooth structural detail. Some types of flaws (e.g., those produced by lack of fusion in welded components) or in partial joint penetration (PJP) welds may be considered sharp for practical purposes, although they are not atomically sharp in theory. Following work by McMeeking and Parks (1979), if the crack width is significantly less than the CTOD, which is on the order of 0.25 mm for low-carbon structural steels, of a material, then it may be conservatively treated as sharp for the purposes of fracture prediction. The notion of SSY is interpreted in the context of its effect on the accuracy of traditional fracture mechanics; it is generally understood to mean that the plastic zone is well confined (typically in the vicinity of the crack tip) such that traditional fracture mechanics parameters (K_I , J_I , or CTOD) bear unique correspondence with crack tip stresses. Thus, SSY for structural components may be defined because it is for the validity of standard KIC or JIC tests. With this background, various structural engineering scenarios are discussed.

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Scenario Type 1: Structural Components with a Sharp Crack

For structural components with a sharp crack, two sub scenarios are distinguished by whether the component is loaded monotonically or cyclically. Fig. 9 shows a PJP welded connection with a lack of- fusion flaw, and a pre-Northridge moment connection with a pre-existing flaw, both of which may be considered structural components with a sharp crack. Scenario 1a: Sharp-Cracked Structural Component Subjected to Monotonic Loading An example of this is a PJP welded butt splice (Fig. 9). In these types of situations, the appropriate fracture model is motivated by the extent of yielding. The specimen size limitations for the use of linear-elastic fracture mechanics [as outlined in ASTM E399 (ASTM 2013a)] or elastic-plastic fracture mechanics [as outlined in ASTM E1820 (ASTM 2013c)] may be used as general guidelines to assess the size of the structural component (given material yield stress and fracture toughness) in the context of KIC or JIC validity. If determined to be valid, standard LEFM or EPFM approaches (outlined in prior discussion) are suitable, where the toughness demand is determined from finite-element simulations and the capacity is determined either through standardized testing or through correlations such as the one outlined in Eq. (3). In sharp-cracked structural components where traditional fracture mechanics approaches are inapplicable (this is common in structural components with sharp but shallow cracks and high material toughness), local criteria are necessary. Specifically, this may include the history-based VGM [Eq. (6)] or its state-based counterpart [Eq. (11)]. Chi et al. (2006) and Kanvinde et al. (2008) indicated that for these situations, either of these approaches is more effective compared with traditional approaches. However, because sharp-cracked situations involve steep strain gradients near the crack tip, the fracture predictions are sensitive to the characteristic distance l_c , which must be calibrated accurately; the aforementioned references describe procedures to accomplish this. Because cleavage fracture is always possible, it is also prudent to apply the corresponding criterion (e.g., the Weibull approach or the RKR model) concurrently with the ductile fracture models. Scenario 1b: Sharp-Cracked Component Subjected to Cyclic Loading In this case, the geometric configuration is similar to Scenario 1a, except that the loading is cyclic. In this situation, the nature of cyclic loading is the primary factor in selecting the optimal modeling strategy. If the situation can be categorized as high cycle fatigue (a bridge deck under vehicular loading or a mechanical component), then fatigue crack growth may be calculated through established procedures such as the Paris fatigue law (Paris and Erdogan 1963). For every computed crack length and applied load (either an overload or the peak tensile load of the cyclic loading), fracture may be evaluated by assuming this to be equivalent to Scenario 1a (i.e., a precracked body under monotonic loading), with the final cycle being considered as the monotonic load. With the context of Scenario 1a, traditional EPFM and LEFM or local approaches may be applied (as discussed in the previous section), depending on the level of anticipated yielding. If the component is subjected to earthquake-type ultralow cycle fatigue, then large-scale yielding is anticipated even during the cyclic loading, with a small (<20) number of cycles to failure. This situation may be interpreted as one of fracture due to cyclically induced damage, rather than one of fatigue crack growth. In this case, local criteria such as SWDM [Eq. (10)] or CVGM [Eq. (8)] may be applied in a manner similar to the VGM for Scenario 1a.

Scenario Type 2: Structural Components without a Sharp Crack

The possibility of fracture without the presence of a sharp crack is of special interest in civil structures. This may occur in zones of stress or strain concentration around holes or blunt notches, in zones of local buckling, or simply in smooth structural members subjected to large inelastic strains. The selection of modeling strategy for structural components without a sharp crack is more straightforward than for cracked components because traditional fracture mechanics are invalidated at the outset due to the absence of a sharp crack and the high likelihood of large-scale yielding. Moreover, without the presence of a sharp crack (and the associated increase in stress triaxiality) it is unlikely that fracture will initiate due to cleavage (recall that high triaxiality raises the principal stresses that are responsible for cleavage). This implies that local criteria for ductile fracture are usually applicable. Within these local criteria, the specific criterion may be selected based on combination of factors including (1) nature of loading (monotonic or ULCF), (2) stress state, defined by triaxiality and Lode parameter, and (3) evolution of stress-state through loading history, affecting whether history-based or state-based criteria are used. Criteria such as the SWDM are most general, being valid for cyclic and monotonic loading, a range of stress states, and also loading history effects. However, these models also require the calibration of additional parameters, which are redundant in specific scenarios (high triaxiality, monotonic loading). Notable applications of these models include safety assessments of liquid storage tanks under seismic loading (Prinz

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and Nussbaumer2012) and bolted steel connections sensitive to block shear (Wen and Mahmoud 2015). Even in smooth components, the initiation of fracture (which may be predicted by a local criterion for ductile fracture) reflects material separation and the formation of a sharp crack. Subsequent to this, fracture propagates as a sharp crack, which typically includes some extent of ductile tearing followed by transition to cleavage.

IV. CONCLUSION

This report provides an overview of the state of the art in fracture prediction for steel structures in civil infrastructure. This consists of models developed over decades for varied application scenarios and within different technological and computational settings, resulting in the absence of a unifying methodology for fracture prediction across all scenarios. In view of this, the mission of the report is to contextualize what often seems like a patchwork of discordant methodologies, with the ultimate objective of providing guidance for effective simulation of fracture in the structural engineering profession. For this purpose, it is critical to develop an understanding of the fracture micro mechanisms themselves and the relationship of various models to these mechanisms. The various models include the traditional approaches of linear-elastic and elastic-plastic fracture mechanics, which are phenomenological, and the more recent local approaches, which seek to simulate the micro mechanisms at a lower scale. The local approaches do not suffer from some limitations of the traditional approaches, but are challenging to effectively implement within a practical setting. Optimal strategies for predicting fracture in common structural scenarios are outlined, recognizing trade-offs between the complexity and cost of implementation and the accuracy of prediction. While major advances have been made in terms of fracture criteria for a range of conditions (stress states, loading types, micro mechanisms), the framework itself has significant limitations. With advances in computational technology, fracture mechanics continues to evolve to address these limitations and other issues faced by the structural engineering profession. Complementarily, because the profession emphasizes accurate performance assessment rather than prescriptive code-based design, it is anticipated that fracture mechanics will meaningfully integrate into the design process.

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