Mechanics of Materials 101 (2016) 81–92

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

Research paper

On the statistical modeling of cleavage fracture toughness of structural steels

Wei-Sheng Lei*

Currently at Applied Materials, Inc., Bldg. 81, M/S 81305, 974 East Arques Avenue, Sunnyvale, CA 94085, USA

ARTICLE INFO

Article history:
Received 11 November 2015
Revised 14 July 2016
Available online 19 July 2016

Keywords:
Cleavage fracture
Fracture toughness
Statistical model
Plastic yielding
Structural steels

ABSTRACT

The prevailing statistical models of cleavage fracture of structural steels for probabilistic risk assessment all infer a two- or three- parameter Weibull distribution of fracture toughness with a modulus of 4 and a fixed-value threshold independent of temperature and plastic constraint. This work starts with a critical review of three major statistical models of cleavage fracture toughness, namely the Beremin model, the Master Curve approach and the Prometey Unified Curve model, with a focus on their theoretical foundations, followed by a brief introduction and further extension of a newly developed statistical cleavage fracture toughness model. Then the Euro fracture toughness dataset is employed to assess these four models. The basic formulations of all the three existing models are not normative and defy the assumption of plastic yielding as a prerequisite to cleavage fracture. The key points of the new model are validated by the Euro dataset that cleavage fracture toughness does not necessarily obey the Weibull statistics while the threshold fracture toughness varies with temperature and plastic constraint.

1. Introduction

Cleavage fracture toughness of structural steels is featured by significant size effect and large variation. Since the details of the crack-tip stress field cannot be always fully characterized by the dominant first-order singularity term controlled by a single conventional fracture mechanics parameter (e.g. the stress intensity factor K_I, J-integral), the size or constraint effect on the fracture toughness K_{Ic} or J_{Ic} is inevitable. This has long been calling for a methodology to reliably transfer the fracture toughness data from small-sized laboratory specimens to real structural components. Attempts have been made to compensate the constraint effect by incorporating a stress triaxiality parameter (e.g. the T and Q stress) (O' Dowd and Shih, 1992). However, due to its deterministic nature, such a two-parameter approach cannot handle the considerable scatter of cleavage fracture toughness. The inherent scatter of cleavage fracture toughness of structural steels in the lower shelf and ductile-to-brittle transition temperature regime for specimens of nominally identical configuration tested at a same temperature under same loading conditions (loading mode and speed) necessitates a probabilistic method, often known as the local approach, to assessing cleavage fracture toughness.

Compared to the fracture mechanics theory based global approach, the local approach evaluates cleavage fracture as a cumulative probabilistic event of individual volume elements in a solid controlled by certain microscopic failure mechanisms. The microscopic failure mechanisms themselves are described by some micromechanical fracture criteria, which assume that failure can take place in any volume element so long as a certain critical stress/strain state is established. Hence, the local approach is expected to be capable of dealing with both the constraint dependence and the variation of fracture toughness in aid of numerical calculation. Since the early 1980s, tremendous efforts have been put to develop statistical models of cleavage fracture in structural steels to address these two aspects together. As a result, two models have been most widely adopted, namely the Beremin model (Pineau, 2006) and the “Master Curve” method (Wallin, 1985, 1993, 2002; IAEA, 2005; Wallin and Laukkanen, 2008). In addition, the Prometey Unified Curve model (Margolin et al., 2003, 2008, 2013, IAEA, 2005) has also gained increasing attention.

1.1. Significance of the work

At a high level, all the three models are based on the weakest link postulate and the understanding of the dominant microscopic cleavage fracture mechanisms, and end up with employing a two- or three- parameter Weibull statistics with a modulus (m_K) of 4 and fixed-value threshold (K_{min}) to describe the statistical distribution of cleavage fracture toughness (K_{Ic}), which leads to a much concise scaling law of the size effect on cleavage fracture toughness in the form of $B \cdot (K_{Ic} - K_{min})^4$. Here B is specimen

* Corresponding author.
E-mail address: leiws2008@gmail.com

http://dx.doi.org/10.1016/j.mechmat.2016.07.009
0167-6636/

thickness, $K_{min} = 0$ for the Beremin model, while $K_{min} = 20\ MPa\sqrt{m}$ in the Master Curve approach and $K_{min} = 26\ MPa\sqrt{m}$ in the Prometey Unified Curve model.

These three statistical models have been gradually evolved into design theories and made significant engineering impacts. Specifically, the influence of the Beremin model is exemplified as follows:

- The European Structural Integrity Society (ESIS) has recommended a procedure *ESIS P6-98* for the determination of the Beremin model parameters (Pineau, 2006).
- Based on the Beremin model, the Japanese Welding Engineering Society (JWES) has developed a standard WES 2808 (Minami, 2014) for assessing brittle fracture in steel weldments subjected to large cyclic and dynamic strain during earthquake.
- The International Organization for Standardization (ISO) has published a standard ISO 27306:2009 (Minami, 2014), which specifies a method for converting the crack-tip opening displacement (CTOD) fracture toughness obtained from laboratory specimens to an equivalent CTOD for structural components, taking constraint loss into account according to the Beremin model.
- The Standardization Administration of China has published a national standard GB/T 30064–2013 based on ISO 27306:2009.
- The Beremin model is also used to determine certain constants in the empirical formulae to compute fracture toughness in the Structural INTegrity Assessment Procedures for European Industry (SINTAP) or the European Fitness-for-service Network (FITNET) procedures.

The Master Curve method has been developed into a procedure for mechanical testing and statistical analysis of fracture toughness of structural steels in the transition region. It has been gaining acceptance throughout the world within the nuclear energy industry as well as other industries dealing with critical structures as manifested below:

- The American Society for Testing and Materials (ASTM) has published the ASTM E1921-11 standard for the Master Curve method — *Standard Test Method for Determining of Reference Temperature T_0 for Ferritic Steels in the Transition Range*.
- The International Atomic Energy Agency (IAEA) has sponsored its eighth coordinated research project (CRP-8), *Master Curve Approach to Monitor Fracture Toughness of Reactor Pressure Vessels (RPV) in Nuclear Power Plants*, to foster the application of the Master Curve approach for RPV structural integrity assessment in nuclear power plants, and published the Technical Reports Series No.429 entitled *Guidelines for Application of the Master Curve Approach to Reactor Pressure Vessel Integrity in Nuclear Power Plants* (IAEA, 2005).
- The Master Curve approach has been also used in the fracture toughness estimation procedures in some other structural integrity codes including the European SINTAP and FITNET, the British R6 procedure, and the European unified technical design rules for steel structures EUROCODE-3 code developed by the European Committee for Standardization in 1993.

The Prometey Unified Curve model (Margolin et al., 2003, 2008, 2013; IAEA, 2005) has been adopted in the Soviet (Russian) Code PNAE G-7-002 entitled *Regulations for Strength Analysis in Nuclear Power Plant Equipment and Piping* for the water-water energetic reactor (WWER)-type reactors, which were widely built and used mainly throughout Russia and the Eastern European countries.

The safety design of key engineering structures such as nuclear reactor pressure vessels and offshore oil platforms against catastrophic failures typically specifies a very low failure probability in the order of 10^{-6}–10^{-7}. Particularly, since essentially all commercial light water reactors use ferritic low alloy steels for the construction of RPVs, which have been identified as the most critical component of a nuclear power plant, the assurance of their structural integrity under continued operation and accidental conditions is critically stringent. Taking the typical Basic Safety Limit (BSL) of 10^{-3}–10^{-4} as the numerical criterion for measuring the annual accident frequency, the conditional cleavage probability is around $10^{-7}/(10^{-3}$–$10^{-4}) = 10^{-3}$–10^{-4} as a rough estimate. However, in reality it is impossible to directly test or duplicate such a low probability failure event at full-size scale at an affordable cost. The practical solution is to rely on an indirectly verifiable design theory or model. This places a very high expectation on the rigorousness and consistency of the design theory. Since cleavage induced brittle fracture is the most hazardous failure mode with potentially catastrophic consequences, it is reasonable to carefully inspect the critical conclusions derived from these established models. Of particular interest are the following three questions:

- Is there a solid theoretical foundation for the description of cleavage fracture toughness using a two- or three- parameter Weibull statistics?
- Why does the two- or three- parameter Weibull statistics of fracture toughness bear a modulus (m_K) of 4?
- What is the fundamental justification for a fixed-value threshold of fracture toughness (K_{min})?

These concerns are raised due to the recent findings in Lei (2016a) on statistical modeling of cleavage fracture and a subsequent revisit to the pioneering work of Landes and Shaffer (1980) on empirically describing the cleavage fracture toughness with the two-parameter Weibull statistics.

A self-consistent cumulative failure probability model for cleavage fracture of ferritic steels was formulated in Lei (2016a), which abides by the assumption of plastic deformation as the prerequisite to the occurrence of cleavage fracture. Subsequently, a cleavage fracture toughness model was derived, which suggests that the cleavage fracture toughness distribution does not necessarily follow a two- or three- parameter Weibull distribution. Furthermore, instead of being an intrinsic constitutive material constant, the threshold value of cleavage fracture toughness varies with temperature and geometrical constraint, which is contradictory to basic assumptions of a constant threshold cleavage fracture toughness in the Master Curve approach and the Prometey Unified Curve model. The findings led to a revisit to the earlier work on statistical characterization of cleavage fracture toughness. Landes and Shaffer (1980) first adopted the two-parameter Weibull statistics to describe cleavage fracture toughness in the transition regime as below.

$$P = 1 - \exp\left[-\left(\frac{J_C}{J_0}\right)^{m_J}\right] = 1 - \exp\left[-\left(\frac{K_{Jc}}{K_0}\right)^{m_K}\right] \tag{1}$$

Here J_c is the critical J-integral at cleavage fracture, K_{Jc} is the corresponding critical stress intensity factor, J_0 and K_0 are scalar parameters for normalization, m_J and m_K are Weibull slope or modulus coressponding to J_c and K_{Jc}, respectively. $m_K = 2m_J$ due to the relationship $K_{Jc} = \sqrt{EJ_c/(1-\nu^2)}$, where E and ν are Youngs' modulus and the Poisson's ratio, respectively. They found that $m_J \approx 5$ when fracture toughness is represented by the critical J-integral J_c. Accordingly, if the fracture toughness is reprensted by the critical stress intensity factor K_{Jc}, the equivalent value of Weibull slope should be $m_K \approx 10$. This high value of m_J or m_K was attributed to insufficient amount of data replication and the improper use of the two-parameter Weibull model in place of a three-parameter Weibull model to obtain m_K (McCabe, 1991). However, even with sufficient toughness data points, fitting with a three-parameter