ADVANCING THE STATE OF PRACTICE IN STEEL BRIDGE EVALUATION: APPLICATION OF THE MASTER CURVE AND FITNESS-FOR-SERVICE FOR EXISTING STRUCTURES

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BIOGRAPHY

Dr. William Collins is an Assistant Professor at the University of Kansas. He received his BS, MS, and PhD from Virginia Tech, focusing his studies on steel bridge behavior and performance. After completing his doctoral studies he worked as a Research Engineer at Purdue University. His research and teaching focus on steel structures, with an emphasis on fatigue and fracture related issues.

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Dr. Connor has nearly twenty-five years of experience in the fatigue and fracture evaluation of steel bridges. He is currently an Associate Professor in the Lyles School of Civil Engineering and Director of the S-BRITE Center at Purdue University. During his career, he has researched fabrication flaws, fatigue cracking, brittle fractures, and developed repair strategies for structures for a variety of agencies including state DOT, rapid transit authorities, construction companies, and structural consultants.

SUMMARY

When managing an inventory of large, complex steel bridge structures, it is inevitable some will contain defects introduced in construction, fabrication, or service. The management approach to addressing these defects can have a large impact on the ability of a given structure to remain in service. This is of extreme importance in the context of highway infrastructure, as aging bridges and other structures are a critical component of transportation systems. Further, the majority of existing steel bridges in the USA are over 50 years old. Other industries around the world have adopted rational practices to deal explicitly with defects found in structural components, thereby improving their management of large inventories of structures and structural components. Advances in the understanding of fracture mechanics allow for these detailed, probabilistic approaches.

The following paper introduces and discusses two concepts for improved evaluation and management of transportation infrastructure. First is the master curve concept, which is used to characterize fracture behavior and material toughness. Second is fitness-for-service, which is an approach to directly assess flaws in structural components. Additionally, an example demonstrating the application of these methods for steel bridges is presented.

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Introduction

Extending the service life of the existing steel bridge inventory is of great importance to owners, engineers, and end users. At times, the possibility of brittle fracture in an older bridge has led to concerns for some owners. Unfortunately, the understanding of fracture behavior and its application to steel structures is quite limited among the majority of practitioners. Further, many steel bridges were built prior to the implementation of the modern provisions for controlling fatigue and fracture currently included in the AASHTO and AWS Specifications (1). This is of particular importance in an industry where the introduction of defects during construction, fabrication, or service is inevitable. Fortunately, the field of fracture mechanics has seen many advances over the past four decades, allowing for a greater understanding of brittle and ductile fracture.

In many other industries, fracture is treated explicitly, similar to other steel bridge limit states, such as buckling or strength. Advances in the field of fracture mechanics on both the resistance and demand side include the characterization of material fracture properties and the advanced analyses available for use in structural evaluations. For example, the master curve concept, as related to the characterization of material toughness, is one such advancement widely utilized in the oil and gas, nuclear, and offshore industries. The master curve allows for the characterization of fracture behavior in the brittle and brittle-ductile transition region, the behavior regime of most structural steels at service temperatures. Included in the master curve characterization are the size effects associated with cleavage fracture, as well as the distribution of fracture initiation sites throughout a material. It is the recognition of distributed initiation sites which allows for the statistical treatment of cleavage fracture behavior.

Additionally, advancements beyond the concepts of the master curve have also been realized. Many industries around the world have developed standardized procedures for the application of fracture mechanics concepts to structural components containing cracks and defects that can be idealized as crack-like. These techniques are generally referred to as fitness-for-service (FFS) procedures and provide information about the ability of a structure to safely function in the presence of a flaw.

Fracture Behavior

In general, fracture mechanics is the study of a solid under a given loading condition in the presence of a crack. Because discontinuities act as stress raisers, fracture can occur at load levels well below that expected to cause yielding in the component. An infinitely sharp crack creates a mathematical singularity, and the applied state of loading is characterized by stress intensity factor, K. The ability of a material to resist the applied stress intensity is known as fracture toughness.

Fracture toughness of steels used in structural applications can be categorized in three different behavior regimes. Each regime is highly dependent on temperature. At low temperatures, steel fractures in a brittle, cleavage mechanism. This region of constant fracture toughness is known as the lower shelf of fracture behavior. In contrast, at warmer temperatures fracture behavior is typically characterized by plasticity and ductile tearing. Fracture toughness values at warmer temperatures reach a plateau of upper shelf behavior. Between the two shelves is the transition region of fracture behavior. In the transition region small changes in temperature can result in substantial changes in fracture toughness. Additionally, behavior in the transition region can be controlled by cleavage fracture, ductile tearing, or a mixed-mode combination of each. As a result, fracture toughness in the transition region can be highly variable. Each regime is schematically represented in Figure 1.

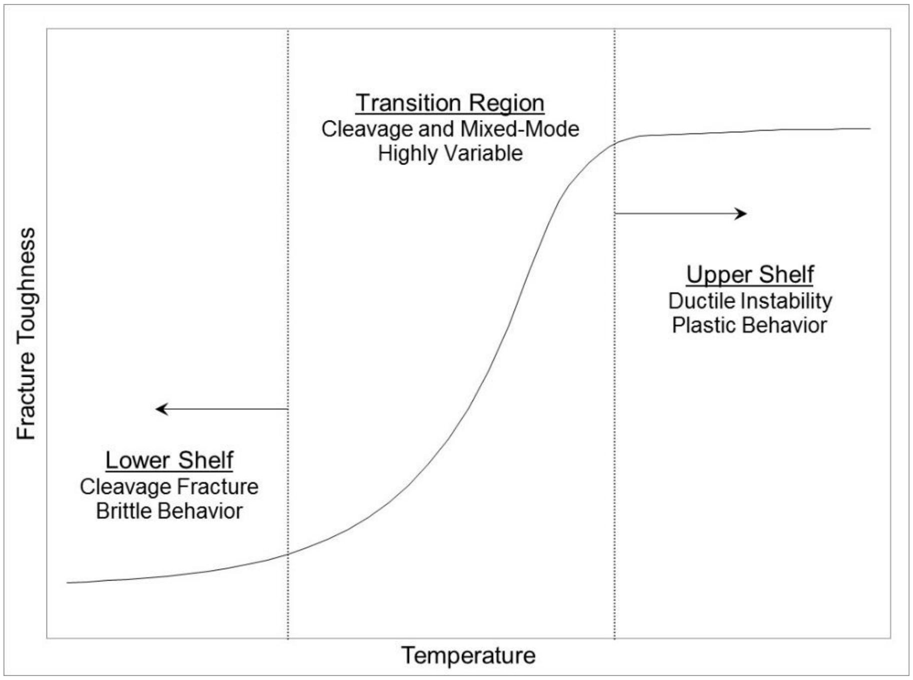

Figure 1. Temperature dependence of fracture behavior

Master Curve Introduction

The transition region, with extreme variability in behavior, has historically been difficult to characterize. This has made fracture mechanics-based analysis of structural components extremely difficult. Although considered to be a globally homogenous material for structural analysis, microstructure discontinuities exist locally throughout all structural steels. Precipitates, grain boundaries, or inclusions create such discontinuities and act as initiation sites for cleavage fracture. As initiation sites are randomly distributed throughout the material, cleavage fracture can be treated as a stochastic event. Recognizing this, application of the master curve methodology allows for the statistical treatment of fracture toughness in the lower shelf and lower transition regions, which can lead to probabilistic assessment of structural integrity. The concept of the master curve has been shown to accurately describe fracture toughness data of multiple grades of base steel and weld metals, including historic US bridge steels (2, 3).

Background and Development

Landes and Shaffer first attributed scatter in fracture toughness data to the impact of material microstructure (3). Observing initiation sites on the failure surfaces of fracture specimens, they were able to represent probability of failure at a given toughness level with a two-parameter Weibull distribution model. As thicker materials inherently have a larger dispersion of initiation points, they will exhibit lower apparent toughness than thinner components of the same material. To account for the effect of material thickness, Landes and Shaffer developed a size correction to account for flaw distribution along a crack front. The work by Landes and Shaffer was all done in terms of the J-integral, an elastic-plastic parameter representing the energy release rate during a fracture event.

Building upon the work of Landes and Shaffer, Wallin applied the same principles to fracture toughness in terms of stress intensity and fracture toughness, *K*, instead of the J-integral (2). Additionally, identification of an absolute minimum fracture toughness for structural steel allowed for the introduction of another parameter in the statistical model, and a three-parameter Weibull distribution was adopted. The size correction and scatter models were applied to a curve based on an empirical fit of the temperature-fracture toughness relationship, and the concept was first standardized in 1997. Current standardization of the master curve concept can be found in ASTM E 1921-13, "Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range (5)." A more thorough explanation of master curve methodology development can be found in McCabe, et al. (6)

Aspects of Master Curve

Three key features of the master curve are essential for a basic understanding of its application. These features are the shape and location of the curve itself, the scatter of the data about the curve, and the correction of fracture toughness values for material size effects.

An exponential curve representing the relationship between temperature and fracture toughness forms the basis of the master curve concept. Typically presented as median fracture toughness or 50 percent probability of failure, the master curve has been shown to have the same shape for all ferritic steels. The master curve can be defined by a single temperature corresponding to a specific toughness value because the shape of the curve does not change. This temperature is known as the reference temperature, T_o, and corresponds to a median toughness of 91 ksi√in (100 MPa√m). Median fracture toughness described by the master curve as a function of temperature, *T*, is given by:

$$K_{Jc(med)} = 27.3 + 63.7e^{[0.01055(T-T_o)]}$$

where $K_{Jc(med)}$ is the median elastic-plastic critical fracture toughness in ksi√in, and temperature values are given in degrees Fahrenheit. A typical master curve with reference temperature of -22 °F (-30 °C) can be seen in Figure 2.

Fracture toughness data scatter is described by a three-parameter Weibull distribution, as previously discussed. Statistical tolerance bounds about the exponential master curve can be calculated by:

$$K_{Jc(0.xx)} = 18.2 + \left[ln\left(\frac{1}{1-0.xx}\right)\right]^{1/4}\{10 + 70.1e^{[0.01055(T-T_o)]}\}$$

where *0.xx* represents the desired probability of failure. Calculated tolerance bounds of 5 and 95 percent are shown in Figure 2.

To account for initiation sites throughout the material matrix, specimen size is normalized by adjusting fracture toughness values. Nomenclature used to designate thickness of fracture mechanics specimens is xT, where 'x' is the specimen thickness in inches. Master curves are commonly presented in terms of 1T thickness. For structural evaluation, toughness values should be adjusted to normalize for the actual thickness of the material comprising a structural component. The thickness correction is performed by the use of:

$$K_{Jc(x)} = K_{min} + \left[K_{Jc(o)} - K_{min}\right]\left(\frac{B_o}{B_x}\right)^{1/4}$$

where $K_{Jc(x)}$ is the fracture toughness adjusted to a desired thickness, B_x, K_{min} = 18 kis√in (20 MPa√m), and $K_{Jc(o)}$ is the fracture toughness at thickness B_o.

Once a reference temperature determination has been made for a given material, fracture toughness values for a given thickness, temperature, and probability of failure may be chosen for use in a probabilistic fracture mechanics evaluation of a structural component.

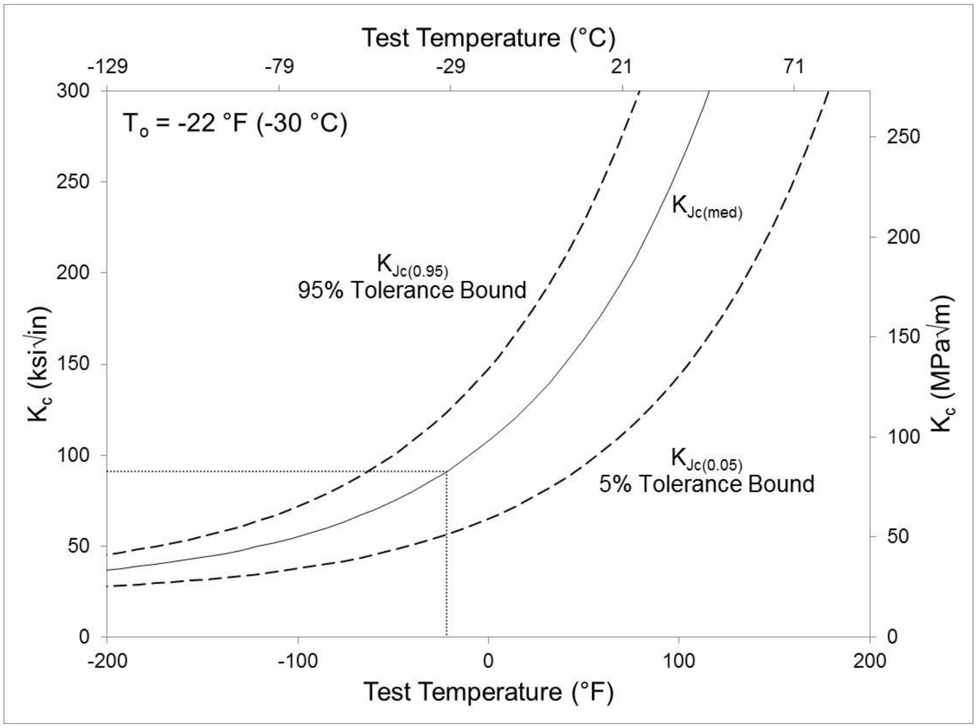

Figure 2. Typical master curve with tolerance bounds

Fitness-for-Service Introduction

The concept of fitness-for-service is an overall approach to evaluating structures and structural components with existing flaws. As presented above, the master curve methodology can be used within an FFS evaluation. Fitness-for-service, also commonly referred to as fitness-for-purpose (FFP), examines the ability of a structural component to serve its intended function in the presence of the defect.

Currently, neither the AASHTO Bridge Design Specifications nor the Manual for Bridge Evaluation include codified guides for assessing structures with flaws (7, 8). The oil and gas, offshore, and nuclear industries have well established practices regarding FFS. The two most widely accepted and employed specifications for FFS are the BS 7910:2013 "Guide to methods for assessing the acceptability of flaws in metallic structures" from the British Standards Institute and the API 579 "Fitness-For-Service" from the American Petroleum Institute (9, 10).

Fitness-for-service procedures typically have multiple methods of varying rigor known as assessment levels or options. Selection of a particular option is dependent on the information available during the assessment. Basic assessments using assumed, simplified material properties and simple stress states form the basis for lower levels of analysis. Progressing through the options allows for the inclusion of exact material properties and complex stress states. Analysis options can include the use of true fracture toughness test data, post-yield strain hardening properties, and residual stress gradients caused by welding. Lower level options with less rigorous analysis are considered to be more conservative than higher level options. Typical assessments will begin at the lowest option. If a structural component fails a low-level option, the assessment can proceed through the stages of rigor in an effort to obtain a more refined, successful analysis.

Although the focus of an FFS evaluation revolves around strength and fracture as final limit states, the mechanisms that lead to these must be considered. These mechanisms include fatigue crack propagation, creep, and corrosion of a structural component. Although important, evaluation of creep and corrosion in an FFS evaluation are beyond the intended scope of this paper. Additionally, details of evaluation for fatigue crack growth are not presented. Any investigation of components with crack-like defects should include a time-dependent fatigue crack growth analysis. The analysis must be performed in the context of critical crack size, as determined through an FFS evaluation.

As FFS deals primarily with the final limit states of strength and fracture, it is common practice to analyze structural components with methods examining both. One method employed in FFS analyses use what is known as a failure assessment diagram (FAD) to evaluate structural integrity. Although other FFS methodologies exist, such as crack driving force curves, this paper will focus on FADs as they are the most prevalent tool used in FFS evaluations.

Failure Assessment Diagrams

Failure assessment diagrams were first developed in the 1970's for the UK nuclear industry as part of their flaw assessment protocol, designated R6 (11). Simultaneous evaluation of both fracture and plastic failure was not performed in prior assessment methodologies (12). Simultaneous evaluation allowed for the consideration of the interaction between brittle fracture and plastic collapse, and the successful use of FADs in the nuclear industry has led to their adoption and use in other industries and standards.

An FAD examines failure due to brittle fracture on one axis, and plastic collapse on the other. This is done through normalized ratios of applied load and material resistance. For fracture, the ratio of crack driving force to material fracture toughness, K_r, is used. Plastic collapse is analyzed by the ratio of equivalent load applied to the uncracked ligament of a component, known as the reference stress, and the material yield strength, L_r. Plotting the FAD along with this assessment point for the component in question provides an indication of structural integrity. If the assessment point falls within the region formed by the FAD, the component is deemed safe. Failure is indicated when the assessment point lies outside of the FAD region. This is shown schematically for a generic FAD in Figure 3.

The amount of detail included in an analysis, FFS level or option, will determine the shape of the diagram. Depending on the specification, a low level analysis may not consider the interaction of fracture and plastic collapse, resulting in a rectangular FAD. Higher levels will consider the interaction through a function based on post-yield fracture mechanics (13, 14).

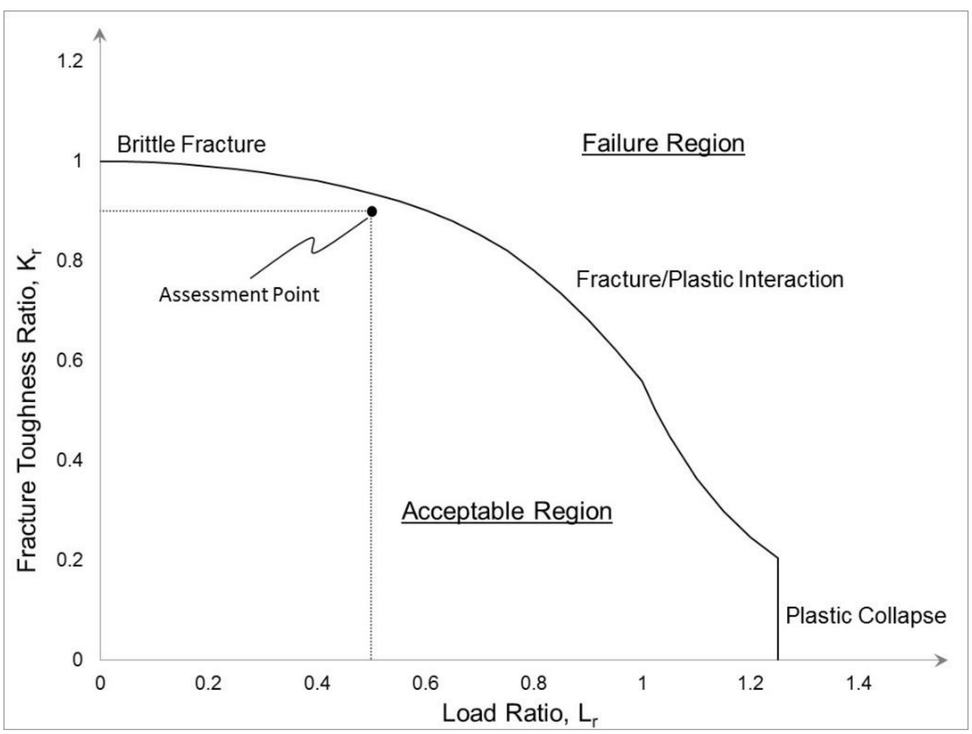

Figure 3. Typical failure assessment diagram

Application Example

Fitness-for-service procedures, although not prescribed for steel bridges, are well established and published in various manuals (9, 10). An example is presented of how FFS, coupled with the master curve, can be used in the evaluation of steel bridge components. This example uses equations found in BS 7910 (9). However, any accepted FFS methodology will produce similar results. Although the example represents a realistic FFS application, it is hypothetical and meant to only be illustrative in nature. The applied concepts are widely applicable to steel bridge components; however, the specific flaw characteristics, member geometry, and material properties used were chosen to ease calculations for the purposes of the example. Additionally, no consideration is given to the probability of detection (POD) in this example. In a real FFS evaluation the engineer should consider POD when an acceptable flaw size determination is made. This example assumes an inspector can reliably detect a crack that is 0.125 in. (3.2 mm) or longer. In cases where the critical crack size is smaller than can be reliably detected based on POD data, either the inspection method should be modified, the structure should be pre-emptively retrofit, or an alternate strategy to control fracture should be employed.

A tension member on a riveted, built-up truss is being examined. Located in AASHTO Zone I, the lowest anticipated service temperature (LAST) for the bridge is 0 °F (-18 °C). The component under consideration is a 0.5 in. (12.7 mm) thick by 12 in. (305 mm) wide plate of A36. The rivets used in the structure are nominally 0.75 in. (19 mm) with 0.875 in. (22.2 mm) holes. Previous testing of the steel has shown the material to have Charpy V-Notch (CVN) impact energy absorption values of 20 ft-lbf (27 J) at a temperature of -50 °F (-46 °C).

Combined dead and service live loads on the bridge cause the components to reach 55 percent of design yield stress, while allowed permit load vehicles may induce up to 75 percent of design yield stress. To make determinations concerning allowable loads, it is necessary to evaluate the structure at multiple stress levels.

Although inspection shows no signs of fatigue damage, it is impossible to see beneath the rivet caps. For this reason, the owner requests an assessment of structural integrity in the event a fatigue crack is present below the rivet head. Based on inspection capabilities, a fatigue crack would need to grow out of a rivet hole to a length of 0.375 in. (9.5 mm). A crack of this size would extend approximately 0.125 in. (3.2 mm) beyond the rivet head. Thus, a through-thickness fatigue crack is assumed to extend beyond each end of the rivet hole, perpendicular to the direction of applied loading, as shown in Figure 4.

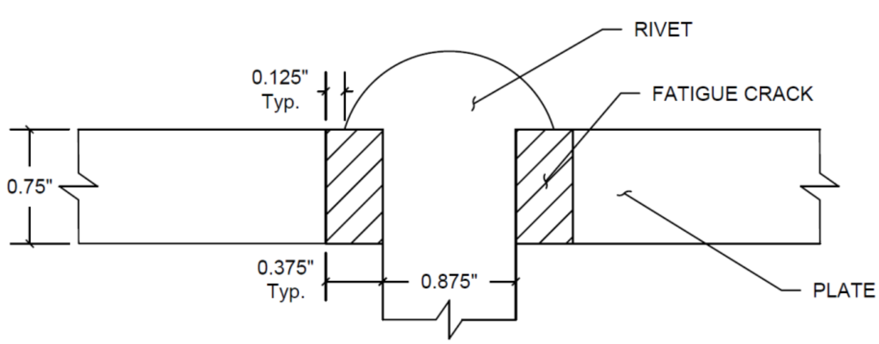

Figure 4. Section view of assumed through-thickness fatigue crack at rivet hole

Employing Option 1 level of analysis, a FAD envelope is developed and plotted. This option does not require detailed material stress-strain data, but simply develops a conservative curve based on nominal design values of F_y = 36 ksi and F_u = 58 ksi (248 and 400 MPa).

Assessment ratios for fracture and plastic collapse are calculated for the plate in question, requiring the calculation of reference stress occurring on the uncracked ligament of the plate. Reference stress is computed using the equations provided in BS 7910, based on the specific geometry of the component. For the example, the reference stress at a global stress of $0.75F_y$ is equal to 31.2 ksi (215 MPa). The assessment ratio L_r is calculated by dividing the reference stress by the material yield strength, resulting in a value of 0.867.

The applied stress intensity, or crack driving force, acting on the assumed flaw is also required. Closed-form solutions for stress intensity are once again provided in BS 7910. For the given geometry and $0.75F_y$ loading, the crack driving force is 46.8 ksi√in (51.4 MPa√m).

Although the master curve methodology utilizes true fracture toughness, K, data, there are ways to employ the methodology in the absence of actual K data. Numerous correlation methods exist to estimate material reference temperature directly from CVN data, and many FFS procedures include a CVN-to-T_o correlation (15). For the example, a correlation from BS 7910 was chosen which equate CVN test temperatures related to a specific energy level, 20 ft-lbf (27 J), to a 1T master curve reference temperature. The correlation results in a 1T reference temperature of T_o = -37.4 °F (-38.5 °C).

From T_o, the master curve allows for a size-corrected determination of a material toughness value at a specific temperature with selected probability of failure. A five percent probability of failure with a size correction to 0.75 in. (19 mm) thickness results in a material toughness of 82.7 ksi√in (90.8 MPa√m) at the LAST of 0 °F (-18 °C). Dividing crack driving force by the fracture toughness of the material provides K_r = 0.772 at $0.75F_y$.

The calculated assessment ratios are used to plot a point on the FAD, shown in Figure 5. Additionally, assessment points for applied stresses of 0.55 and $0.65F_y$ are also plotted using the five percent probability of failure for fracture toughness. At load levels producing 55 and 65 percent of yield, the assessment points fall within the FAD envelope, indicating the structure is capable of tolerating a crack of the given size and shape subjected to those levels of loading. In contrast, the assessment for $0.75F_y$ falls outside of the FAD, indicating failure of the component for the conditions and probability of failure assumed.

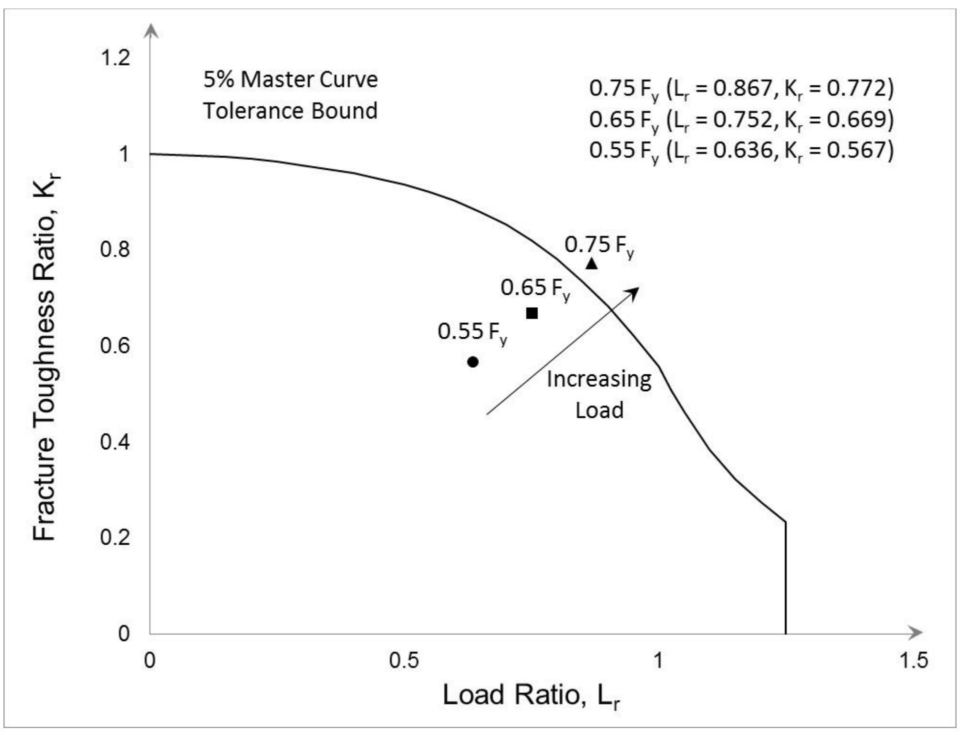

Figure 5. Example FFS evaluation with FAD and 5% fracture tolerance bound

Facing this scenario, the engineer has multiple options for further analysis. Taking advantage of actual material properties, a higher level of FFS analysis may provide an acceptable result. However, with no additional data beyond the nominal tensile values and CVN data provided in this example, it is not possible to apply any higher level of analysis.

To make a more informed, probabilistic assessment of structural integrity, additional master curve tolerance bounds can be used to analyze the probability of failure due to fracture. In this context probability of failure refers to the percentage of fracture specimens expected to fail at a given load and temperature combination, not the probability of global failure. Calculation of global probability of failure would include statistical measures of loading, as well as variance in tensile properties and other variables.

Assessment points were calculated for the given example using fracture toughness tolerance bounds of 1, 5, 10, 15, 20, and 25 percent probability of failure. These points are plotted on the FAD, presented in Figure 6, and indicate the relative levels of structural integrity for varying probabilities of fracture failure. All tolerance bounds provide acceptable results at a load level producing 55 percent of yield. At $0.65F_y$ the one percent tolerance bound produces an unacceptable result, while the five percent assessment is within the FAD envelope. Again, neither the one nor five percent tolerance bounds for $0.75F_y$ produce an acceptable assessment. However, when employing a ten percent fracture tolerance bound, the 75 percent of yield load level falls within the FAD envelope, indicating a successful analysis. Although not shown in Figure 6, the analysis at a $0.75F_y$ load level is successful when the fracture toughness tolerance bound is reduced to eight percent.

An additional analysis, similar to the examination of fracture tolerance bound effect, can quantify the impact of crack size changes on the structural integrity. Not shown in this example, a crack size study could be beneficial in a structural assessment, and would simply require running the same analyses for various crack sizes, resulting in more assessment points on the FAD. Adding the additional variable of crack size to the assessment provides additional information for owners and engineers to make rational management decisions.

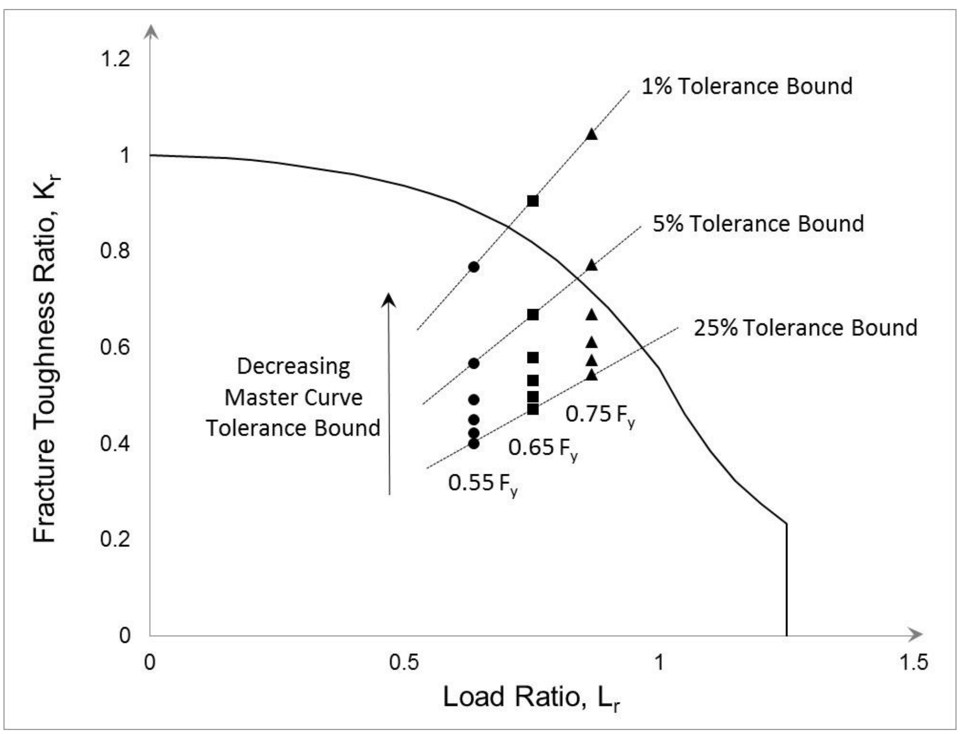

Figure 6. Example FFS evaluation with varying master curve tolerance bounds

Conclusions

Management of any large inventory of complex structures must be able to account for flaws and defects. This is no less true for the steel bridge industry than it is for the oil and gas, nuclear, or offshore industries. The approach taken in the management of these structures has a large impact on their ability to adequately function throughout the desired service life.

The master curve methodology and fitness-for-service concepts, commonly used in other industries, were presented within the context of steel bridge evaluation. While the master curve concept deals directly with fracture mechanics and material characterization used in structural evaluation, fitness-for-service is a global approach for evaluating structural components with existing flaws. Combining the advantages of each concept gives bridge owners the ability to treat fracture explicitly in a statistical evaluation.

Information provided by the FFS analysis can be used by the owner and engineer to make rational, informed decisions concerning the management of a structure. As shown in the provided example, FFS analysis allows an owner to determine appropriate levels of risk inherent in the operation of the bridge. The ability to probabilistically manage risk can be used to provide consistency between the design of new bridges and the operation of existing structures.

Although not currently standardized in the steel bridge industry, there are efforts underway to employ both the master curve methodology and FFS techniques to steel bridges. Specifically, Transportation Pooled Fund project 5(238), Design and Fabrication Standards to Eliminate Fracture Critical Concerns in Two Girder Bridge Systems, is examining the use of the master curve in an integrated fracture control plan for steel bridges. Additionally, NCHRP project 14-35, Acceptance Criteria of Complete Joint Penetration Steel Bridge Welds Evaluated Using Enhanced Ultrasonic Methods, is investigating the use of FFS tools in determining rational acceptance criteria for welds. While still underway, both of these efforts may lead to the eventual adoption and specification of these methods for steel bridge applications.

Embracing the master curve and fitness-for-service concepts has the potential to promote and better characterize safety and reliability while extending the service life of the aging inventory of steel bridges, as well as influencing the design and construction of future structures.

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