Small Specimen, Accelerated Fracture Mechanics Test Methods for Failure Analysis

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ABSTRACT: *Innovative methods of extracting test specimens while minimizing the compromises in fracture mechanics analysis often requires imaginative and creative loading conditions to duplicate the in-service fracture conditions. Accelerated test methods to conduct time dependent crack growth measurements in a short time also becomes a critical requirement.*

The purpose of this paper is to provide an overview of the modified fracture mechanics test methods with specific examples of how modified specimens were fabricated and utilized in the analyses. It will explained how an accelerated test methods developed on a government funded Small Business Innovative Research Program (SBIR) is utilized to measure fracture toughness with small specimens and life parameters of crack initiation threshold, KIscc, and $K_{threshold}$ *for fatigue in a very short time. These techniques have been applied to conduct failure analyses of welded HY 130 steel structures, turbine bolts, gas regulator springs, and chrome-plated aircraft pistons.*

INTRODUCTION

In order to measure fracture mechanics parameters on failed structural components that are often in small pieces, a quantitative small specimen test methods had to be developed that can quickly measure life parameters that characterize subcritical crack growth both due to fatigue and environmentally assisted stress cracking. The loss of daily production of hardware can become very expenses to the point that the time to conduct a failure analysis becomes key to the financial salvation of the company.

Remnant pieces of a fractured structure do not always leave pieces of sufficient size to machine a specimen of a size that corresponds to the geometry requirements for measuring the critical linear elastic stress intensity parameter; in fact, if a component is properly designed, the dimensions will be such that only plane stress conditions exist in the part and not plane strain. Not all pieces are flat or can have flat pieces machined form them. Time for performing the test is also limited by the demands of production.

A failure analysis utilizes the Scanning Electron Microscope to determine the failure mode and identify the fracture origin. The SEM investigation for the origin involves looking for a defect that can be a case crack or lap that initiates a fatigue failure or a corrosion pit initiates a stress corrosion (SCC) crack. If a defect cannot be detected, the crack apparently initiated by exceeding the crack initiation threshold in fatigue or stress corrosion. To determine if the root cause is a material defect or a design defect, or if the operating stresses exceeded the anticipated stresses, the crack initiation fatigue or stress corrosion threshold of the actual material must be measured.

To be measured, both of these parameters require a large number of specimens, several test machines, long test times and specimens that exceed the size of the remnant pieces from the failed component. Hence, to complete a failure analysis within a reasonable time frame, small specimens and accelerated test procedures are required.

This paper demonstrates how small specimens all evolving around modifications of the 10 x 10 x 55 mm Charpy square bar can be used to rapidly measure fracture toughness parameters of K_{Ic}. K_{Id}, K_{Iscc}, K_{ctod}, T_d (dynamic tear modulus), crack initiation thresholds in fatigue and stress corrosion, and if necessary subcritical crack growth measurements in fatigue and stress corrosion, not to mention that they serve as excellent specimens for hardness measurements, microstructural examination and SEM exemplars. Utilizing unique loading profiles, the long term threshold parameters in fatigue and stress corrosion can be measured in an accelerated manner (less than one week) using a small number of specimens.

Small Specimen

All fatigue precracked (fpc) specimens begin with a notch specimen. Advantage can be taken of the testing time spent in introducing a sharp crack to measure the crack initiation threshold in either fatigue or stress corrosion. The ideal small specimen for a failure analysis investigation is the 10 x 10 x 55 mm Charpy sized specimen. Much data and machines already for measurement of the ASTM Standard E 23 impact tests and relationships to dynamic fracture toughness, K_{Id}. In addition, the specimen is included in ASTM Standard E 399 (E 1820) with a parameter, the specimens strength ratio in bending, R_{sb}, primarily as a means of indexing the fracture toughness for elastic-plastic conditions that result in invalid E 399 linear elastic fracture toughness measurements. This parameter is further defined and characterized as the specimen strength in bending in ASTM Standard E 812. Figure 1 is the specimen as described in ASTM Standard E 812.

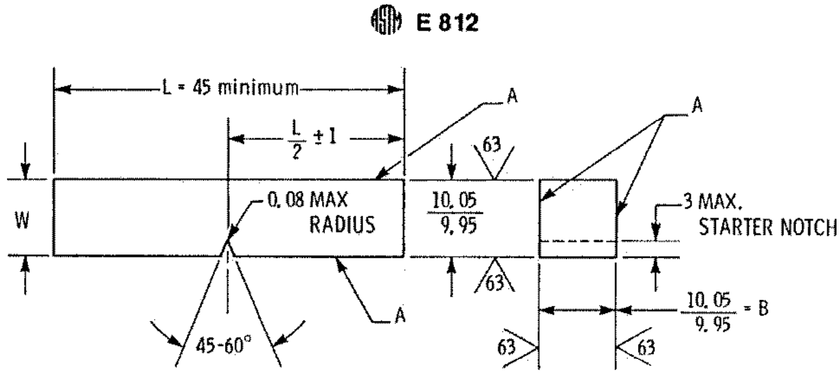

Figure 1: Precracked Charpy Specimen per ASTM E 812.

Figure 2 taken from an NMAB Report 328 [1] illustrates the value of this small specimen in measuring the fracture toughness beyond the limits of linear elastic fracture mechanics. The correlation between fracture toughness and R_{sb} holds to a ratio of ≤ 2.0 Linear elastic fracture mechanics per E 399 is only valid to a R_{sb} of ≤ 0.8. For Rsb > 2.0, K_{ctod} per ASTM E 1290 as a SEN(B) specimen can be used to measure the fracture toughness. These relationships permit the Charpy square bar to be used over a large range of fracture toughness measurements quite accurately to > 2 x K_{Ic} per E 399.

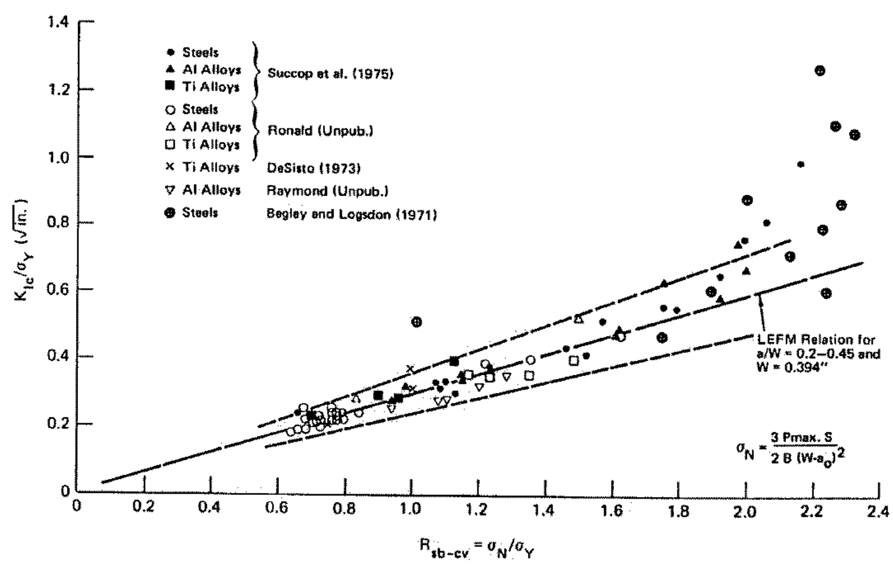

Figure 2: Correlation of valid K_{Ic} with Charpy Specimen Strength Ratio, R_{sb}, from Pre-cracked Charpy Slow Bend test.

Conventional Testing

The time consuming measurement is that of the threshold in either fatigue or stress corrosion. Figure 3 illustrates the region of infinite life or the stress range below the threshold, where no subcritical crack growth occurs either in fatigue or stress corrosion. Run-out or threshold in fatigue is > 10^6 cycles. Run-out or threshold due to stress corrosion cracking (SCC) or hydrogen embrittlement of steels, either internal due to plating or environmental (IHE/EHE) is ≥ 5,000 h (>6 month) for steels greater than 1,200 MPa and ≥ 10,000 h (> 1 year) for steels less than 1,200 MPa per ASTM Standard E 1681. As noted in Figure 3, about 12 specimens are required to determine the fatigue or stress corrosion threshold. Fatigue testing can require as much as several machines and 6-months of testing to establish the threshold.

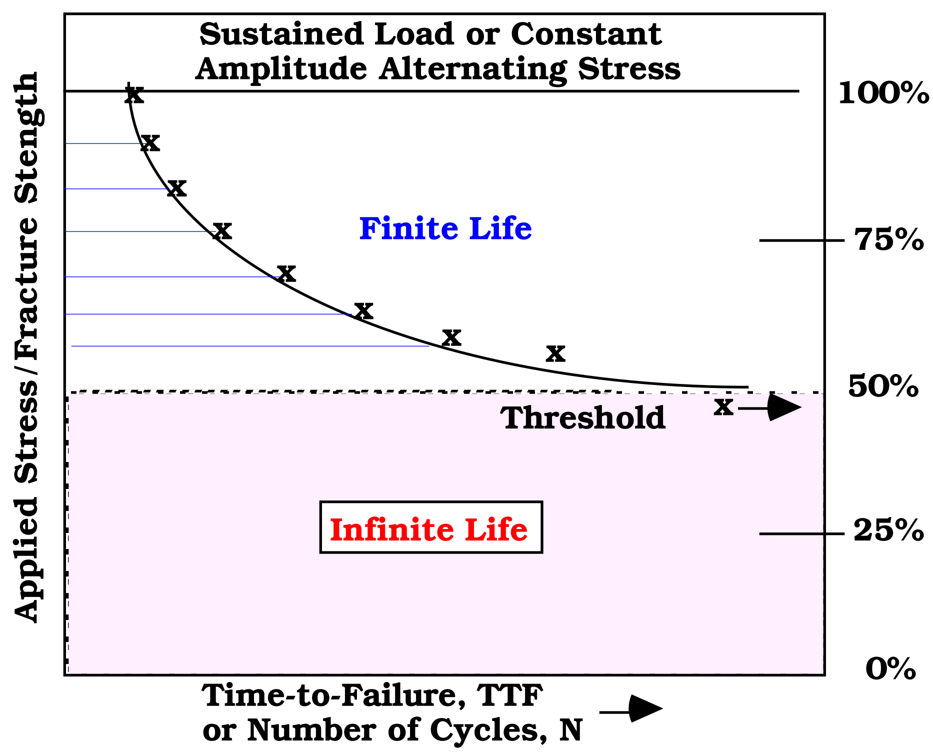

Figure 3: Conventional Loading protocol for measurement of the threshold with an alternating stress in fatigue or sustained stress corrosion.

The number of specimens and test times can be significantly reduced by using an innovative approach to testing. Thresholds in fatigue or stress corrosion can be obtained in ≤ 1 week, using only 3- to 5-specimens.

Accelerated Testing

The accelerated test method for measuring the threshold for crack initiation is an incrementally increasing sustained load combined with a slow strain rate test method as identified in ASTM Standard E 1624.

The loading profile is an incremental or rising step load, RSL™. The test is conducted under displacement control, which results in a region of constant stress intensity during subcritical crack growth. The load is applied in 4-point bending so that the applied moment is a constant, permitting the calculation of stress for irregular shaped surfaces. A rigid testing system is used such that a load drop from a change in compliance is sensitive enough to detect the onset of crack growth. The displacement must be maintained constant at each step. The load is used to monitor displacement. The load is programmable to apply/control step modified, slow strain rate loading profiles at progressively decreasing strain rates.

The step load or strain rate progressively decreases until the crack initiation threshold becomes invariant. Either fpc or notched specimens can be used. Verification testing and equipment specifically built to conduct these tests were developed under a U.S. Navy sponsored SBIR [2].

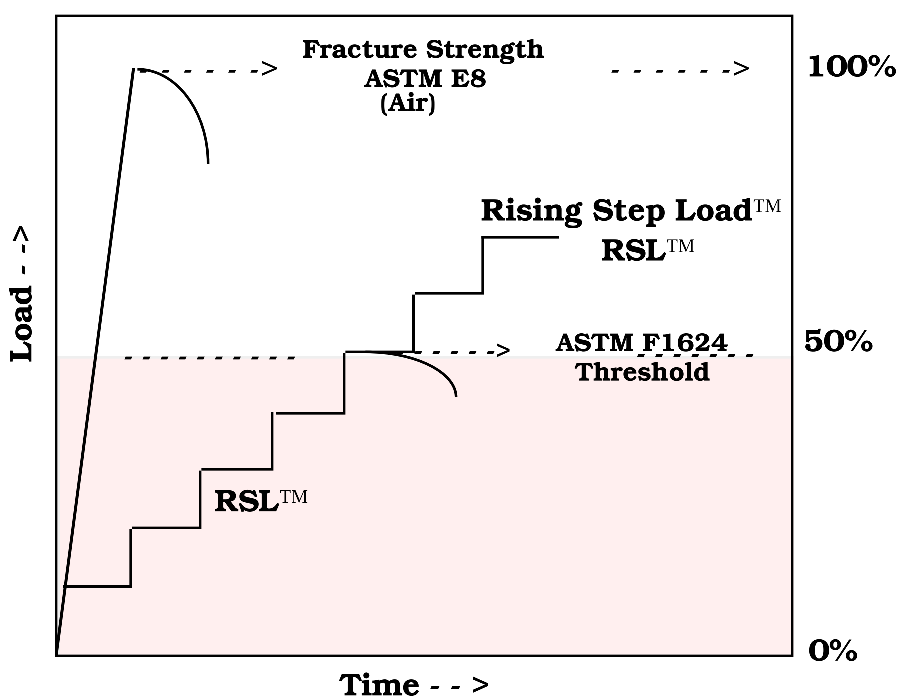

Figure 4: Loading protocol for measurement of the threshold in fatigue or stress corrosion in an accelerated manner.

Bolt Specimens

In addition to testing specimens that exactly conform to Figure 1, actual remnant pieces of hardware such as bolts can be used with adapters to obtain crack initiation and propagation properties. For small diameter bolts, the adapters shown in Figure 4 can be used For large diameter bolts, the remnants of the bolt itself can be used as shown in Figure 5. In both cases, the influence of the thread relative to crack initiation can be characterized and parameters such as residual stress from thread rolling or stress at which case cracking occurs on case hardened surfaces can be measured.

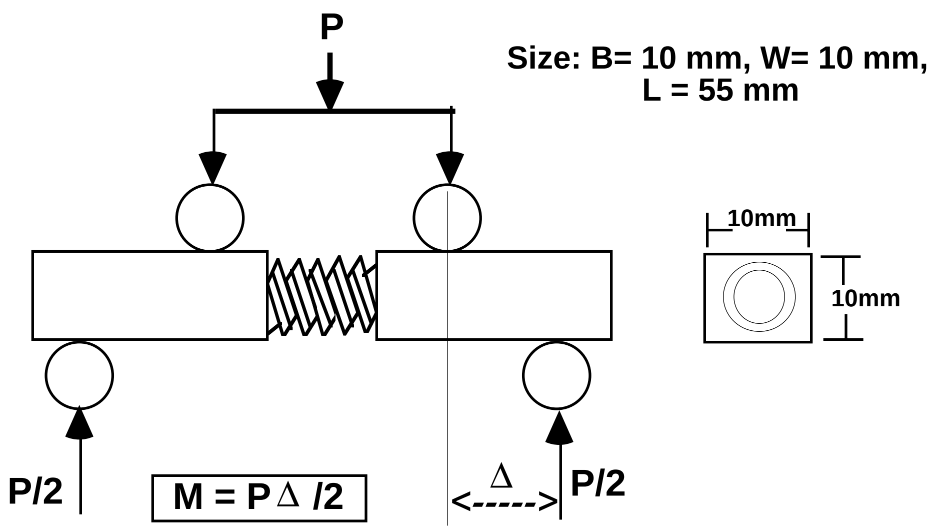

Figure 4: Adapters for testing small bolts in 4-point bending.

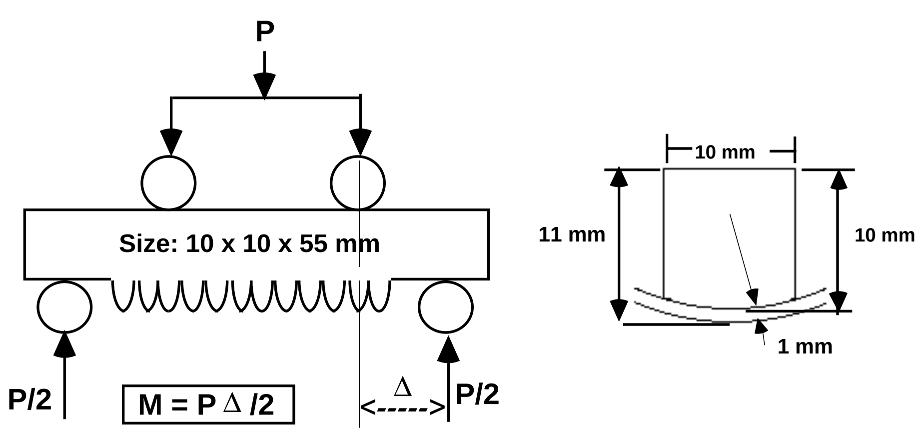

Figure 5: Specimens machined from large diameter bolts for testing as a square bar in 4-point bending,

Accelerated Testing: Fatigue

Depending on the application, fpc or notched, standard Charpy specimens per Figure 1 or modified Charpy specimens per Figure 4 or Figure 5 can be step loaded at 5% of the fracture strength in fatigue at decreasing loading rates obtained by increasing the increment of time progressively from 1 to 2.25 to 4 hours at a constant R-ratio of 0.1 as illustrated in Figure 6. This combination results in maximum test times of 1da, 2da, and 4da or a total of one week. The crack initiation threshold as detected by a drop in load is then plotted as shown in Figure 7. The extrapolation back to zero is the threshold alternating load, stress, or stress intensity. The protocol is taken from Prot [4] and is describe in more detail in ASTM STP 1391 [3].

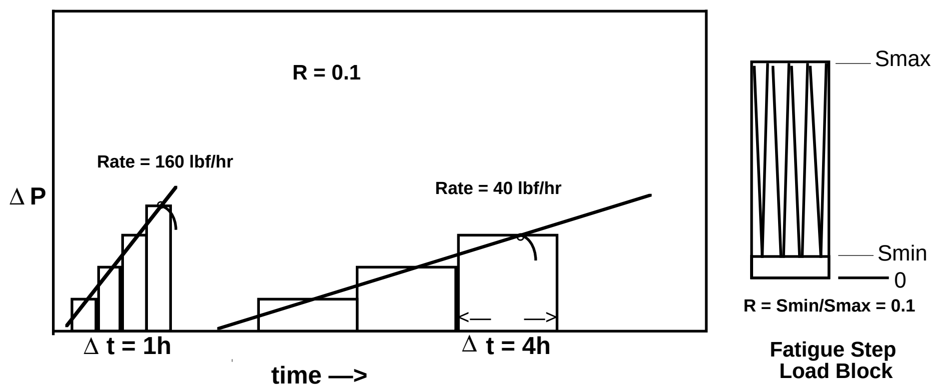

Figure 6: Cyclic Rising Step Load (RSL) Technique at R=0.1

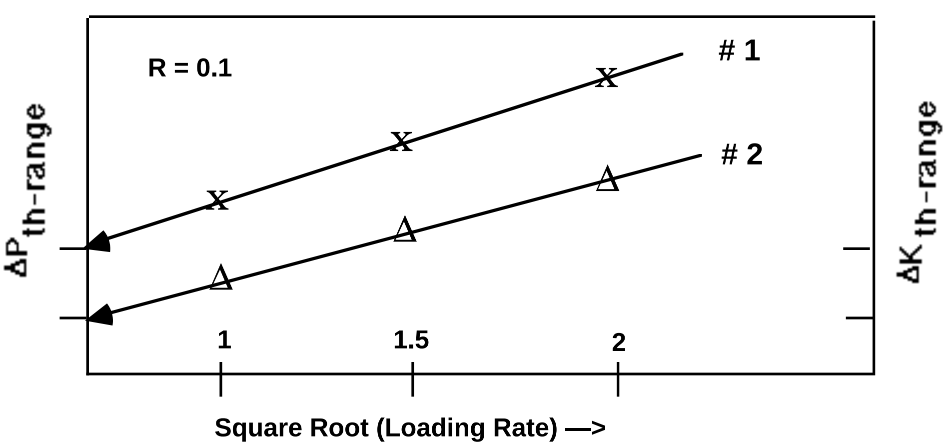

Figure 7: Extrapolation method of determining the threshold fatigue load range ($DP_{th\text{-}range}$) with only three specimens cyclically loaded under displacement control at R=0.1 for two different surface conditions.

Accelerated Testing: Stress Corrosion

The rising step load profile can also be used in stress corrosion testing to measure the threshold for crack initiation as shown in Figure 8. In steels at > 50 HRC, the threshold can be measured in 1da; for the 40 HRC range in 2 da, and for the 30 HRC range in 4 da. The applications of these methods have been used to measure KIscc for HY 130 steels for the Navy and for different coatings on a variety of materials for the Army.

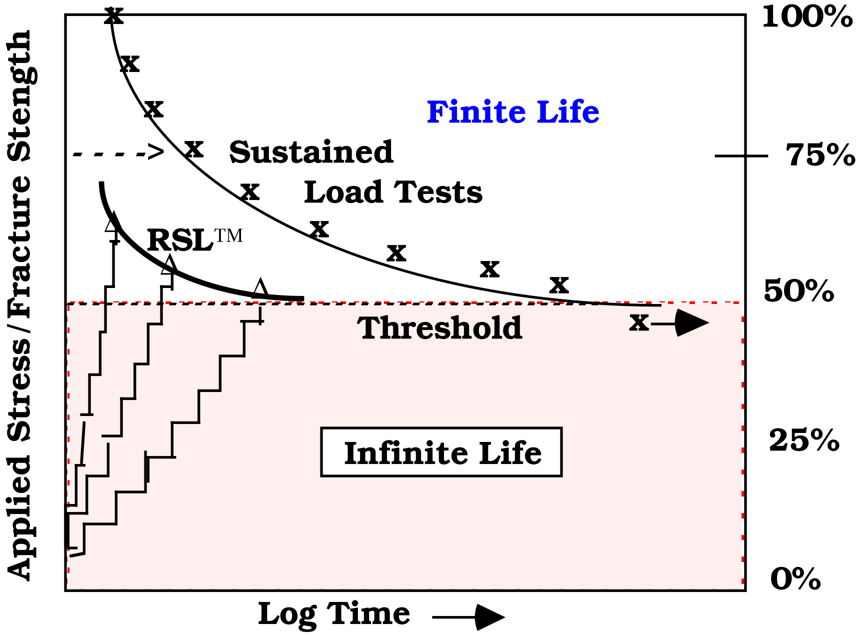

Figure 8: Specimens machined from large diameter bolts for testing as a

References

1 NMAB Report 328 (1976), *Rapid Inexpensive Tests for Determining Fracture Toughness*, p.148, National Materials Advisory Board, National Academy of Sciences, Washington, D.C.

2 Raymond, L. (1993) SBIR Phase II NAVSEA Contract No. N00024-89-C-3833, Final report No. NAVSEA 80058.

3 Raymond, L. (2000) In *ASTM STP 1391*, pp.192-203, Toor, P. M.(Ed)

4 Prot, E. M., (1948) "Fatigue Testing Under Progressive Loading: A New Technique for Testing Materials," *Revue de Metallurgie,* Vol XLV, No.12, p. 481 , English Translation by Ward, E. J., WADC Technical Report 52-148, Wright Air Development Center, Sept., 1952.

5 All of the ASTM Standards can be located on website: www.ASTM.org