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The prediction and verification of ductile crack growth in small test specimens

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THE PREDICTION AND VERIFICATION OF DUCTILE CRACK GROWTH IN
SMALL TEST SPECIMENS

A Thesis

Presented to

The Faculty of the Department of Materials Engineering

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

James Franklin Williams

May 2005

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ABSTRACT

THE PREDICTION AND VERIFICATION OF DUCTILE CRACK GROWTH IN SMALL TEST SPECIMENS

by James Franklin Williams

The ability to predict ductile crack growth in small samples has been of interest to the fracture mechanics community for decades. Previous experimental and theoretical work in the field of elastic-plastic fracture mechanics has enhanced the understanding of decreasing specimen size effects on crack growth predictability. This thesis furthers the understanding of specimen size limitations by experimentally testing three different sized (0.394T, 0.2T, and 0.1T) A516-70 steel three point bend (TPB) samples and modeling them using a computational cell methodology in a finite element analysis (FEA) code called Warp3D. The findings suggest that ductile crack growth prediction may be feasible in experimental samples as small as 0.2T, but not in the comparable FEA model. It is demonstrated, however, that a 0.394T TPB FEA model is capable of predicting crack growth.

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Most of all, I thank Christopher Scott Sinton for creating this opportunity. I would like him to know that I did not forget what he has done for me.

DEDICATION

I dedicate this to my loving father, Donald J. Williams, Sr., who never got to see me finish this work.

If he were here, I would tell him: Thank you Dad for loving and accepting everything about me. Your commitment to changing yourself and becoming such a primary support in my life allowed me to take bigger steps because I knew you were there to catch me if I fell. I miss you greatly every day.

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CHAPTER 1

INTRODUCTION

Fracture toughness is a measure of a material's resistance to crack propagation. The primary influences on toughness are strength (amount of load that can be sustained per unit area) and the size and distribution of flaws (e.g., inclusions) within the microstructure. The strength governs the onset of plasticity in a material while ductile crack growth initiates from existing flaws or defects.

There are several micromechanisms that occur under an applied load that allow ductile crack growth to take place. The first process is void nucleation, followed by void growth, and finally void coalescence (linking). A void nucleates around an inclusion. A sufficient amount of load (stress) must be applied to break the interfacial bond between an inclusion and the host matrix. Under further loading, the voids grow until they reach a critical size. At this critical size, the voids coalesce (link-up) to form ductile crack growth. This ductile crack growth can be stable and can propagate in finite increments. The amount of finite crack growth is directly related to the size and distribution of the inclusions. A schematic of micro-void coalescence is shown in Figure 1.

Fracture toughness is obtained experimentally by testing standard laboratory specimens to determine their resistance to fracture [1]. Alternative predictions of crack growth can be made through modeling using finite element analysis (FEA) codes that

Figure 1. A schematic of ductile micro-void coalescence in front of a crack tip growing from an applied load [2]. Source: C. Ruggieri, “*Numerical Investigation of Constraint Effects on Ductile Fracture in Tensile Specimens*,” Journal of the Brazilian Society of Mechanical Science and Engineering, XXVI, No. 2, 190-199 (April-June 2004).

are capable of predicting ductile crack growth. Both of these methods are discussed in subsequent sections.

1.1 Historical Background in the Study of Crack Growth

Although cracking (failure) of structures has always been a concern in design, the actual study of fracture mechanics was formally established in the mid-1940s as a result of a U.S. ship failure during WWII [3].

In 1943, the early days of World War II, a Liberty Ship made of ferritic steel literally broke in two; this is shown in Figure 2 [4,5]. There were three major causes of the failure:

- 1) Welds in the steel contained crack-like flaws.
- 2) Most of the fracture initiated at regions of high stress concentration.
- 3) The ships were made from low toughness steel (steel which had a low resistance to cracking).

Figure 2. An image of a Liberty Ship taken in 1942 in Portland, Maine [3]. G. MacKenzie, (1985/2005). WW2 Liberty Ships - The Bridge of Steel - Spanning the Atlantic - Linking Britain to America [Online] Available at <http://www.ahoy.tk-jk.net/index.html> (accessed February 2005).

The group that studied the fracture problem of the Liberty ships founded the field of fracture mechanics. This group defined what is now known as linear-elastic fracture mechanics (LEFM), so named because the material behaved very elastically and failed without any deformation. The failure mode of the ship steel was through catastrophic cleavage failure. When a certain critical stress and strain were reached in the steel, it would fail.

In subsequent years, other researchers began to contribute to the area of fracture mechanics. The nuclear industry started to develop programs to monitor the effects of radiation on the ferritic steel pressure vessels that surrounded the reactor cores. Pressure vessel steels operate at temperatures of 550°F and above, significantly higher than the ocean temperatures the Liberty ship failed in.

Ferritic steel's failure mode switches from one of catastrophic cleavage failure at a lower temperature to one of ductile crack growth at higher temperatures. Figure 3 shows the actual material fracture appearance for cleavage and ductile failures. In the early 1970s, Landes and Begley, while working at Westinghouse Research and Development Center, developed a method to measure and predict ductile crack growth by using experimental test specimens made of ferritic steels used in reactor systems [5].

Figure 3. Images showing (a) cleavage fracture and (b) ductile fracture [6].
Source: Vanderbilt University (undated) [Online] Available at <http://mot.vuse.vanderbilt.edu/mse150/Fracture/Ductile> (accessed 5 February 2005).

These efforts founded the area of elastic-plastic fracture mechanics (EPFM). The tests that Landes and Begley performed were standardized and are currently governed by the American Society of Testing and Materials (ASTM) Standards E813 and E1152 [1,7].

While Landes and Begley were developing experimental toughness techniques to measure ductile crack growth, computers were able to model sophisticated tasks and calculate results in a shorter time. Finite element analysis (FEA) was starting to be used for predicting stress states in structures under certain loading conditions. FEA allowed for complicated structures to be analyzed prior to being built, and thereby improved designers' insight. Further development in FEA expanded from elastically responding brittle materials to a more powerful utilization in elastic-plastic (ductile) material response. The initial FEA codes could not model cracks and crack propagation. The models could be distorted under loading, following rules of elasticity, but no method existed for simulating crack propagation. More recently, Robert Dodds *et al.* developed a code called Warp3D that allows a modeled structure to simulate ductile crack growth. For a given load condition, this code calculates the fracture toughness of a material and predicts the associated crack growth [8].

Panontin and Nishioka used Warp3D to model ductile crack growth in A516-70 ferritic steel [9,10]. Through their work, they were able to verify Warp3D's ability to successfully predict ductile crack growth by comparing it to valid experimental test data.

1.2 Predicting and Modeling Crack Growth

Much effort has gone into modeling cracks and predicting ductile crack growth. Small, standard laboratory specimens are used to predict the integrity of structures or to predict the onset of cracking. These specimens are used to determine single parameter (critical) toughness values such as LEFM fracture toughness K_{IC} and the J-integral, J. The test specimens must have sufficient thickness and crack depth to insure that the crack tip lies in a highly constrained bending region. This constraint is necessary in order to obtain a one to one correspondence with the global critical toughness value and the crack tip stress-strain fields. With this approach, standards can establish a lower bound, geometry independent critical values of toughness.

In LEFM, the Mode I crack tip stress-intensity factor, K_I , is used. For a crack in an infinitely large plate under tension, as shown in Figure 4, the Mode I stress intensity factor is:

$$K_I = \sigma \sqrt{\pi a} \quad \text{Equation 1}$$

where a is the crack length and σ is the far field stress in the plate. The fracture toughness of the material, K_{IC} , can be used to determine the fracture load (stress) through comparison of the stress intensity factor.

Figure 4. Infinite cracked plate with LEFM associated equations.

At small amounts of crack tip plasticity or when the plastic zone is a lot less than the material width, W , and remaining ligament, b_0 , fracture toughness is a material property, and LEFM produces good predictability. This dependability on a single parameter is good in LEFM because the fracture mechanism is by catastrophic cleavage failure and there is no stable crack growth beyond the LEFM failure criterion. Figure 5a shows the relative applicability of LEFM or the small scale yielding.

As a material becomes thinner or a specimen becomes smaller, the maximum stress at the crack tip becomes limited by a material's yield strength. The thinner material or the smaller specimens are not as constrained and are not as capable of reaching a critical failure load (stress), and therefore, the material plastically deforms. As a material's plastic deformation or crack tip plasticity becomes significant, the accuracy of LEFM failure predictions decreases. At this juncture, the J-integral or

elastic-plastic J-dominated fracture mechanics needs to be utilized. Figure 5b represents the elastic-plastic region. This single parameter approach yields good results under fully contained plasticity or small scale yielding. Small scale yielding (SSY) occurs when plasticity is small compared to the remaining ligament, b_0 , and has not reached a free surface. This condition is met when the plane strain plastic zone is approximately 50 times larger than a specimen's smallest dimension [1].

As the plastic zone becomes larger compared to the specimen dimensions, the K-dominated zone disappears and LEFM no longer applies. Eventually, even the J-integral becomes invalid and is no longer capable of predicting stresses present at the crack tip. At this point, large scale yielding (LSY) dominates. Figure 5c is a schematic of the LSY region.

During elastic-plastic conditions (where the plastic zone is larger than the allowable in LEFM), the J-integral should predict the crack tip stress and strain. The J-integral is similar to K_I , except it more accurately predicts stress and strains nearer to the crack tip and under conditions where the plastic zone is larger than allowed in LEFM. Measurement of the J-integral during a monotonic quasi-static loading process helps to develop a J-resistance, J-R (J- Δa) curve. Through the use of the J-R curve, the J-integral is used to determine the resistance to fracture. For ductile materials, the predictions for opposed to LEFM. This is because the EPFM method includes the reduction of stress at

(a) Small Scale Yielding

(b) Elastic-Plastic Conditions

(c) Large Scale Yielding

- - Large Strain Region
- - J-dominated Zone
- - K-dominated Zone

Figure 5. Effects of plasticity on crack tip stresses. D is the characteristic length of the material and r is the distance in front of the crack tip. The HRR is the elastic-plastic tip stress strain solution at the crack tip as solved by Hutchinson, Rice, and Rosengren Zone [10]. Source: O.S. Nishioka. 1997. Prediction and Verification of Ductile Crack Growth from Defects in Butt Welds. Master's Thesis, San Jose State University.

the crack tip as a result of local plasticity when calculating the J-integral. When the J-R curve deviates from linearity, it is said that stable crack growth has been initiated. Determining exactly where this deviation occurs is rather difficult so the ASTM Standard E813 dictates that fracture initiation occurs at a 0.008" (200 μm) crack tip opening offset [1]. This number is more for a standard point of reference than actually knowing where initiation begins under loading. This approach is shown in Figure 6 at the crack initiation J-value, J_{IC} . However, as the specimen becomes smaller in both width and remaining crack length, J is no longer repeatable. As a result, test specimen sizes are limited to how small they can be before they no longer produce valid J-values.

Figure 6. An example of a J-integral resistance curve for a ductile material.

Before a crack propagates in a specimen, the stress state, which is extremely geometry dependent, changes under applied loading. As the crack grows and approaches the free surface of the material, the stress state continues to change from a plane strain to a plane stress condition. The crack aspect ratio, which is defined as the ratio of the crack length to the plate width as shown in Figure 7, also changes as the crack grows.

As a crack approaches the free surface, the stresses are no longer fully contained in the material because there is less material confining the crack. At this point constraint can no longer exist. The specimen has reached a condition of a plane stress state. Regardless of where the crack is located in the material, once constraint is lost, plane stress dominates.

Figure 7. A schematic of crack aspect ratio.

1.3 Research Focus

The first focus of this research was to determine the limitations of an existing finite element code for predicting ductile crack growth and toughness in sub-sized three point bend specimens. The second focus of this research was to determine a limiting test specimen size. The research included testing small three point bend (TPB) toughness samples and comparing the results to predictive FEA models. From the results, limitations of the predictive capability and its applicability to experimental samples were determined. Once these limitations were understood, size constraints on both FEA models as well as experimental samples were better defined.

1.4 Thesis Overview

This thesis has both laboratory and theoretical aspects. As a result, there are independent sections focused on experimentation and theoretical applications. The work has been broken down into the following Chapters:

Chapter 1 is an introduction into the world of fracture mechanics and ductile crack growth. It presents the research focus and establishes the direction of the thesis.

Chapter 2 is presented solely to give definitions and acronyms used in fracture mechanics as well as in theoretical modeling.

Chapter 3 discusses the relevant work performed by other researchers, extracting from the work data and conclusions to create a starting point for the work performed here. Once the previous work is summarized, two major questions are posed for this

work. The questions are the focus of this thesis and the work performed here answered these questions.

Chapter 4 presents the research objective and discusses the approach to analyzing the information. This chapter also covers additional information that is needed to expand upon the current level of understanding.

Chapter 5 covers the experimental approach. It defines the type of specimens that were tested as well as the variations in the tests that need to be noted. All data needed for performing the experiments is also presented.

Chapter 6 presents the experimental data and the resultant curves from the testing of the specimens.

Chapter 7 is the theoretical modeling section. It discusses the models that were run and shows the results of the modeling in comparison to the experimental data curves.

Chapter 8 summarizes the conclusions found in the work and recommends future direction for the research.

CHAPTER 2

DEFINITIONS, SYMBOLS, AND ACRONYMS

This thesis work was performed based on the previous work of a number of other researchers. As a result, it was very important to maintain consistency in terminology and nomenclature. The American Society for Testing and Materials has a common terminology standard ASTM E616 – Standard Terminology Relating to Fracture Toughness [11].

The terminology and definitions that are important in this work are listed below. These terminologies were taken directly from ASTM E616 and work by Nishioka [10,11].

Characteristic Length/Distance - The mean distance over which fracture processes must occur before a crack can be said to have propagated, or grown incrementally.

Constraint - A condition wherein the material is unable to deform until material around it deforms first. For example, material near a crack is at a higher stress state than the surrounding material. As a result of the higher stresses, the crack tip material tries to elongate in the direction of loading and contract in the orthogonal directions, but is held in place by the surrounding material. This condition is called constraint.

Plane strain - Stress state which results in non-zero strains in two orthogonal directions and zero strains in a third. A simple example of plane strain is a thick hexagonal beam where large deformations and associated strains in the thickness direction are constrained from occurring

by other material in the thickness direction. Plane strain conditions, if they occur, tend to be located at the center of materials, away from the free surface.

Plane Stress - Stress state which results in non-zero stresses in two orthogonal directions and zero stresses in a third. A simple example of this situation is deformation of a thin flat plate. Since a thin flat plate has very little stiffness in the through thickness direction, it is incapable of carrying load in that direction; therefore, the surface normal stress is zero. Plane stress conditions occur at the free surface of materials.

A number of symbols and letter notations are used throughout this work. The relevant ones are listed below.

<u>Symbol</u>	<u>Description</u>
ϵ	True strain
σ_0	Yield Stress
ν	Poisson's Ratio
a	Crack length
b_0	Remaining (uncracked) ligament, $W-a$
B	Specimen Thickness
B_e	Effective Specimen Thickness
B_N	Net Specimen Thickness
D	Characteristic Length
e	Engineering strain
E	Modulus of Elasticity

f_E	Critical void volume fraction
f_0	Initial void volume fraction
f_n	Volume fraction of void nucleating particles
J	J-integral
J_{el}	The elastic portion of the J-integral
J_{pl}	The plastic portion of the J-integral
J_{IC}	The elastic-plastic fracture toughness. This is the critical J-integral in Mode I direction.
K_I	The Mode I stress intensity factor
K_{IC}	Elastic fracture toughness. This is also called the Mode I critical stress intensity factor.
L	The length of the crack front
M	The constraint parameter
W	Plate width

The following is a list of common abbreviations/acronyms that appear throughout this thesis.

Acronyms

ASTM	American Society for Testing and Materials
CT	Compact tension specimen
COD	Crack opening displacement

CVN	Charpy V-notch specimen
DENT	Double edged notched tension specimen
EPFM	Elastic-plastic fracture mechanics
FEA	Finite element analysis
FEM	Finite element modeling
HRR	Hutchinson, Rise, and Rosengren
J-R	J-resistance curve: toughness, J vs. change in crack length, Δa
LEFM	Linear elastic fracture mechanics
LLD	Load line displacement
LSY	Large scale yielding
NASA	National Aeronautics and Space Administration
SENT	Single edge notched bend specimen
SSY	Small scale yielding
TPB	Three point bend specimen, also shown as 3PB

CHAPTER 3

PREVIOUS WORK

3.1 Mechanisms for Modeling Ductile Crack Growth

Under applied stress, ductile crack growth in ferritic steels follows a multi-step, micromechanical failure mode that involves interacting and simultaneous mechanisms [4,10,12,13]. These steps are summarized below and are shown schematically in Figure 8. The first step is the nucleation of micro-voids by fracture or decohesion at larger inclusions or second phase particles. Although other microstructural effects such as dislocations and low-angle grain boundaries participate in void formation, the inclusions play the dominant role. In ferritic steels, the inclusions are typically manganese sulfides or aluminum oxides. Smaller inclusions exist in these steels, but play less of a role in the crack process [12]. Growth of these micro-voids is the second micromechanical process and coalescence of the micro-voids is the third process. This coalescence is the joining of two or more voids resulting in the formation or propagation of a crack.

The features of these micromechanical processes play a fundamental role in understanding how a crack grows. Consider two materials with identical strength properties and different inclusion sizes. In a material with small inclusions (or low initial void fraction), a higher applied stress is required to cause void growth, and hence, more energy is required to grow the crack. For larger inclusion (or larger initial void fraction) materials, lower stress and less energy is required to cause a crack to grow.

Figure 8. A schematic of ductile micro-void growth.

Less energy is needed because the larger inclusions essentially represent the initial void fraction. With low decohesion energies, the inclusions are not significant in creating voids, only in that they represent the initial void fraction. This explains the effect that the inclusion size has on crack growth. In addition, the average spacing between inclusions dictates the finite increment that a crack grows under applied loading. Larger spacing between inclusions, or voids, increases the finite amount of crack growth. However, much more energy is needed to cause interaction of voids that are spaced farther apart because there is more material to deform and to absorb energy. This relationship between the size and spacing of inclusions controls crack growth response [14].

The micromechanical process described here has been simplified in order to develop a model for use in large-scale computation [12,14,15]. In common ferritic steels such as A516-70, the nucleation of micro-voids occurs at relatively low stresses when

compared to the stresses that develop ahead of a crack tip. This is due to the low cohesive energy of the second phase particles or inclusion. In ferritic steels, manganese sulfides provide preferential nucleation sites. As a result, existing inclusions in the microstructure are modeled as pre-existing voids of some finite volume, thus ignoring the void initiation phase. During coalescence, much smaller inclusions such as carbides assist in the final stages of linking; however, these particles have no appreciable effect on the peak stress capacity of the material [14]. The smaller inclusions influence final separation but contribute very little to the overall energy required to cause a crack to grow. Therefore, once the void fraction reaches a critical size, it is assumed that crack growth has occurred. By not including the void initiation energy and the separation energy, the crack growth model is simplified.

Crack growth under tensile loading is macroscopically planar and directed along a symmetry plane. The crack growth often shows an uneven zigzag at approximately 1-2 times the spacing between larger voids, or approximately the characteristic length, D [2]. Outside of the thin layer, shown in Figure 8, void growth is very small and does not affect the material response. As a result, only the thin layer about the symmetry plane needs to be modeled.

3.2 Prediction of Crack Growth Using Computational Cell Methodology

Computer modeling of ductile crack growth started in the mid-to-late 1980s at the University of Illinois with the development of the finite element analysis (FEA) code, Warp3D, developed by Koppenhoefer and Dodds [8]. Warp3D employs a

micromechanical model, known as the Gurson-Tvergaard or G-T Model, for predicting crack growth [4,8,10,16,17]. The G-T method of finite element analysis is unique in that the size of elements along the crack front is determined by the material in which the crack front is contained. Typically, element size in FEA is chosen to minimize calculation time without sacrificing accuracy of results [18]. In the G-T void growth model, the accuracy of stress and strain predictions are still dictated by the element size, however, the element size is now coupled with the characteristic length of the material. This characteristic length, D , is the length of material over which a critical void density, f_E , must be reached before a crack can grow. As a result, the element size for a material becomes fixed regardless of the dimensions of the model.

Xia and Shih applied the concept of the G-T void growth model in FEA analysis and coined the technique the “computational cell methodology” [14,19,20]. The computational cell model approach is shown schematically in Figure 9. Since the crack grows along a plane 1-2 times the characteristic length scale, the computational cell methodology models this layer as a void-containing volume with an initial void fraction of f_0 . Material outside the computational cells, the “background” material, follows a conventional flow theory of plasticity and remains undamaged by void growth in the cells [21,22]. Under applied stress, once the critical void fraction, f_E , is reached, the crack grows by the amount D . Recall that D is associated with the mean spacing between the larger inclusions and is considered a material property. By using known experimental data, the values of D , f_0 , and f_E can be determined for a given material. Once determined,

Figure 9. (a) A schematic of void-containing elements in a slab along the projected crack growth line; and (b) a sub-element that uses $D/2$ for computing that is obtained from a symmetry plane about the initial crack [23]. Source: L. Xia, C.F. Shih and J.W. Hutchinson, “*A Computational Approach to Ductile Crack Growth Under Large Scale Yielding Conditions*,” *Journal of the Mechanics and Physics of Solids* **43(3)**, 389-413 (1995).

these parameters become characteristic properties of the material. In Figure 9, it is shown that through symmetry, the modeled cell size becomes $D/2$, or one-half the characteristic length.

3.3 The Gurson-Tvergaard Theory

Tvergaard proposed the yield criterion equation that represents the computational cell model used for crack growth prediction [10,18,24]. This model was based on previous work performed by Gurson [8,18]. The yield criterion, Equation 2, is represented below:

$$\Phi = \left(\frac{\sigma_e}{\sigma_Y} \right) + 2q_1 f \cosh\left(\frac{3q_2 \sigma_m}{2\sigma_Y}\right) - (1 + q_3 f^2) \quad \text{Equation 2}$$

This equation represents an element yield criterion, Φ , that is a function of the von Mises macroscopic stress, σ_m ; the current material flow stress, σ_Y ; the matrix equivalent stress, σ_e ; and the void volume fraction, f . This equation takes into account material softening because as the void volume fraction in a material moves toward zero, the yield criterion goes toward zero as well.

Under applied loading, void nucleation and growth result in increasing void volume fraction. A crack propagates when the yield criterion is exceeded. This occurs at some void volume fraction below 1.0 where the material ligaments between voids are no longer capable of sustaining loading and fail. The q_1 , q_2 , and q_3 values represent material constants for different steels. These constants allow for the yield criterion to be exceeded at a void volume fraction significantly less than 1.0. For most steels, this void fraction failure criterion is around 0.1 to 0.2 [10,12,14,15,17,22,23].

Different steels behave differently and cracks grow at different values of void fraction. For the A516-70 steels, q_1 , q_2 , and q_3 were determined to be 1.25, 1.0, and 1.5625, respectively [10,22].

Material properties required for this methodology include Young's modulus (E), Poisson's ratio (ν), yield stress (σ_Y), the actual measured stress-strain curve, the characteristic length (D), and the initial void fraction (f_0). The background material and the matrix material of the cells generally have identical flow properties. Using an experimental stress-strain curve obtained from conventional tensile specimens, a series of finite element analyses of the specimen are conducted to calibrate values for the cell parameters D and f_0 which bring the predicted stress-strain curve into agreement with the

experiment. Experience with plane strain finite element analyses of fracture specimens to estimate D and f_0 for common structural and pressure vessel steels suggests values of 0.008" (200 μm) and 0.004, respectively [2].

The last parameter that is used in this model is a cell extinction parameter. This cell extinction parameter is the value of the void volume fraction, f_E , where the element is essentially "killed" and no longer part of the computation. When a cell or element is killed, its stresses are all reduced to zero, and the crack is said to have grown one-half of the characteristic length or 0.004" (100 μm). For a number of steels, the value for f_E is 0.15 [10].

3.4 Application and Validation of the Computational Cell Methodology

Using the computational cell methodology in FEA, Xia *et al.* applied the computational cell methodology to two materials [23]. With this approach, they were able to verify the accuracy of the FEA code. The first material studied was A533B pressure vessel ferritic steel. ASTM Standard fracture toughness tests were performed on 2.0" (110 mm) width three point bend specimens (1T TPB) with an initial crack length to W ratio (a/W) equal to 0.6. Figure 10a shows a schematic for a TPB specimen.

A standard fracture toughness test generates a curve known as a J-R (or J- Δa) curve. Toughness, J, is a measure of the amount of energy in pounds per inch (or some other unit of energy such as kilojoules per square meter) that a material has absorbed

Figure 10. Fracture toughness specimen geometries: (a) three point bend (TPB); (b) compact tension specimen (CT); (c) double edged-notched tensile specimen (DENT); and (d) single edged-notched tensile specimen (SENT) [23]. Source: L. Xia, C.F. Shih and J.W. Hutchinson, “A Computational Approach to Ductile Crack Growth Under Large Scale Yielding Conditions,” *Journal of the Mechanics and Physics of Solids* **43**(3), 389-413 (1995).

under an applied load, and R is Δa , the crack growth that has occurred at that amount of absorbed energy. By using the cell methodology in FEA, it is possible to simulate J-R curves provided that the finite element material properties of D , f_0 , and f_E are known in addition to the mechanical properties of stress and strain. The stress-strain response is measured by performing tensile tests in the laboratory. However, determination of the values f_0 and f_E so that the simulated results closely match those of the experimental data requires iteration. This iterative process is essentially a calibration of the FEA code for a given material. The characteristic length, D , can be approximated by measuring the distance between the larger inclusions in the material and taking the average spacing as the value. For A533B steel, iteration determined that the FEA material parameter values

were $D=0.008''$ (200 μm), $f_0=0.005$, and $f_E=0.20$. Figure 11 shows the comparison of the experimental data to simulated data. The same A533B steel material parameters were used to simulate three additional geometries: one inch thick compact tension (1T-CT) specimens, one inch thick double edged notched tension (1T-DENT) specimens, and one inch thick single edged notch tension (1T-SENT) specimens. These geometries are also shown in Figure 10. Table 1 contains a summary of specimen sizes and values. The

Table 1. FEA Material Parameters Used in the Computational Cell Methodology

Material	Ref.	Spec.	Specimen Width, W, in. (mm)	Specimen Crack Length, a_i , in. (mm)	Crack Length Ratio, a/W	Characteristic Length, D, in. (μm)	Initial Void Fraction, f_0
A533B Plate	23	TPB	2.0 (50.8)	1.2 (30.5)	0.6	0.008 (200)	0.005
		CT	2.0 (50.8)	1.2 (30.5)	0.6		
		SENT	2.5 (63.5)	0.95 (24.1)	0.38		
		SENT	2.5 (63.5)	1.05 (26.0)	0.41		
		DENT	2.5 (63.5)	0.88 (22.2)*	0.7		
A710 Plate	23	CT	2.0 (50.8) 4.0 (101.6)	1.2 (30.5) 2.4 (61.0)	0.6 0.6	0.016 (400)	0.002
21/4Cr1Mo Plate	21	TPB	1.0 (25.4)	0.6 (15.2)	0.6	0.012 (300)	0.0035
A516-70 Plate	9	1TCT	2.0 (50.8)	1.2 (30.5)	0.6	0.008 (200)	0.004
A516-70 Weld	10	CT	2.0 (50.8)	1.2 (30.5)	0.6	0.008 (200)	0.001
		TPB	0.75 (19.1)	0.225 (5.7)	0.3		
			0.75 (19.1)	0.525 (13.3)	0.7		

simulation results were compared to experimental specimens, and a high degree of accuracy was obtained for each geometry. The work verified the values for D, f_0 , and f_E and showed that the cell parameters are independent of the geometry.

Xia *et al.* performed additional work on A710 steel using 1T CT and 2T CT specimens with a/W ratios of 0.6. The associated FEA material parameters were

Figure 11. Toughness versus crack length change (J-R). In each plot, the experimental data are on the left and the predicted data are on the right. Specimen type is shown in each plot [23]. Source: L. Xia, C.F. Shih and J.W. Hutchinson, "A Computational Approach to Ductile Crack Growth Under Large Scale Yielding Conditions," Journal of the Mechanics and Physics of Solids 43(3), 389-413 (1995).

determined to be $D=0.008''$ (200 μm), $f_0=0.004$, $f_E=0.15$. Results of this work showed good agreement between simulated and experimental results and are shown in Figure 11 [23].

Gao *et al.* performed similar analysis on 2-1/4Cr1Mo ferritic steel using 1T TPB specimens. Their work also demonstrated excellent agreement between simulated and experimental work [22]. Nishioka and Panontin performed work on A516-70 steel plate using 1T CT specimens, and they also showed excellent agreement between simulation and experiment as shown in Figure 12 [12]. Nishioka researched the applicability of the computational cell model on A516-70 welds. This work was performed using 1T CT specimens and 0.75T TPB specimens.

Figure 12. Toughness versus crack growth for A516-70 steel plate for 1T CT specimens with $a/W=0.6$ and $D=0.008''$ (200 μm), $f_0=0.004$, and $f_E=0.15$ [12]. Source: C. Ruggieri, T.L. Panontin and R.H. Dodds Jr., "Numerical Modeling of Ductile Crack Growth in 3-D Using Computational Cell Elements," *International Journal of Fracture* **82**, 67-95 (1996).

A summary of the FEA material parameters, specimen types, material types, and crack lengths for all the discussed research is shown in Table 1. Table 1 distinctly shows variation in D , and f_0 , indicating that each material has its own unique combination of values. Regardless of the geometry or the size of a specimen, the combination of the material FEA parameters, D , f_0 , and f_E , are the same for a given material. This is because these parameters are considered to be material properties, and hence, do not change. Taking an example from Table 1, for any model using a 516-70 steel, the FEA material parameters would be $D=0.008''$ (200 μm), $f_0=0.004$, and $f_E=0.15$.

Each specimen has a remaining ligament through which a crack can propagate. This remaining ligament (b_0) is the difference between the width (W) and the initial crack length (a_0). This length is divided into cells equal to $D/2$ in width and height as demonstrated by the symmetry of Figure 9. The remaining ligament is converted to remaining elements (cells) by dividing b_0 by $D/2$. For each observed condition, Table 2 summarizes the number of remaining elements for each specimen studied.

As stated previously, FEA is usually approached from a compromise between computational time and accuracy of results. The finer the elements in an FEA model, the higher is the accuracy but the longer is the time that it takes for the computer to calculate the results. In the computational cell methodology, the element size is fixed because it is a material property. Therefore, the question that arises which has been answered with this work is: What is the smallest number of elements (remaining ligament) that can be modeled to obtain accurate predictive results?

Table 2. The Number of Computational Elements in the Remaining Ligaments

Material	Researcher	Spec.	Crack Length Ratio, a/W	Remaining Crack Length, b_0 , in. (mm)	Characteristic Length, D , in. (μm)	Number of Elements in Ligament
A533B Plate	23	TPB	0.6	0.80 (20.3)	0.008 (200)	203
		CT	0.6	0.80 (20.3)		203
		SENT	0.38	1.55 (39.4)		394
		SENT	0.41	1.48 (37.5)		375
		DENT	0.7	0.75 (19.1)		191
A710 Plate	23	CT	0.6	0.80 (20.3)	0.016 (400)	102
			0.6	1.60 (40.6)		203
21/4Cr1Mo Plate	21	TPB	0.6	0.40 (10.2)	0.012 (300)	68
A516-70 Plate	9	1TCT	0.6	0.80 (20.3)	0.008 (200)	203
A516-70 Weld	10	CT	0.6	0.80 (20.3)	0.008 (200)	203
		TPB	0.3	0.53 (13.4)		134

Gao *et al.* demonstrated that 68 elements for the 0.5T TPB specimens predicted crack growth as shown in Table 2 [22]. This was the smallest number of elements comprising a remaining ligament that has yielded accurate results. In this thesis, the FEA computational cell methodology is challenged with smaller sized models; the above posed question has been answered and the number of cells reduced.

3.5 Critical Summary of Computational Cell Application

The previous performed work had given credibility to the use of the computational cell methodology for predicting ductile crack growth. However, the majority of the efforts went into defining parameters for materials and specimens that can be adequately modeled using finite element analysis. An understanding of the limitations of the cell methodology had not been addressed. Prior to the work presented here, there existed no known work that discussed the minimum size of a specimen that was modeled accurately

using the computational cell model in Warp3D. It was adequately shown that the computational cell model was a useful tool for predicting crack growth for the specimens addressed in this section. It was a logical step to develop an understanding of the limitation on model size. The results of the work here have addressed this question.

3.6 Thesis Problem Statement

As stated before, ductile crack growth from an existing crack or defect is the culmination of several micromechanisms that occur under an applied load. These processes are void nucleation, void growth, and void coalescence. Because these micromechanisms are controlled by the spacing and size of inclusions or some other microstructural element, the events that lead to ductile tearing must occur in a finite volume of material. Hence, there is a length scale associated with the ductile fracture process.

One ductile crack growth prediction technique that has been developed is the computational cell methodology, which employs the Gurson-Tvergaard constitutive model for dilatant plasticity. The cell methodology provides the framework that links a realistic void growth model (e.g., the Gurson-Tvergaard model) to the characteristic length scale related to the size of the fracture process zone. It is suitable for the large-scale, three-dimensional (3-D) analyses that are required to predict constraint effects on crack growth behavior in ductile metals.

Ductile crack growth in the cell methodology is confined to a layer of material symmetrically located about the crack plane having a thickness, D , equal to the material's

characteristic length for ductile fracture. D can be estimated from the mean spacing of the larger, void initiating inclusions. The symmetrical layer about the crack plane has cell elements with the dimension of $D/2$ on each side. Each of the elements theoretically contains a spherical cavity, such that it possesses an initial void volume fraction, f_0 . The initial void volume fraction is related to the number and size of inclusions in the material.

Two questions were posed concerning the ductile crack growth process and its prediction using the computational cell model.

- 1) When does characteristic physical length scale “become large” compared to the specimen ligament? The ligament is the remaining length of material for a crack to propagate through before complete failure occurs in a specimen.
- 2) When does element size $D/2$ or computational length scale “become large” compared to specimen ligament?

The first question addresses the physical mechanism of ductile fracture: whether the ductile fracture process can and does occur as specimen size decreases. In bend type specimens specifically, it was anticipated that the ductile crack growth mechanism becomes suppressed when the length scale characteristic of the ductile fracture process becomes comparable to the area of tensile stress ahead of the crack.

Analytically, the question became one of how small a specimen could be before the length scale caused the computation to break down. Since the parameter D was fixed (material property), the number of computational cells decreased as the specimen size being modeled decreased. If, for example, in a two-dimensional analysis, the remaining ligament in a specimen was 0.2” (5.0 mm) and $D/2=0.004$ ” (100 μm), the total number of elements ahead of the crack was 50. If the specimen size was reduced by half, the number of elements was reduced to half of that value, and so on. At some point as the

remaining ligament was reduced, the code was not able to accurately represent the crack tip field in the sample because D was too large to resolve it. This program was successful in determining the limiting number of elements that can be modeled in Warp3D as a remaining ligament and still produce valid results.

3.7 Area of Research

This research focused on FEA models for A516-70 as the material had been fully characterized by Panontin and Nishioka. Panontin and Nishioka investigated A516-70 steel and determined the D value to be approximately 0.008" (200 μm). For element size modeling, Nishioka and Panontin verified the size of the element for FEA modeling was on the order of one-half the size of the characteristic length or 0.004" (100 μm) [10].

In addition to modeling, experimental testing was performed on the ASTM 516-70 steel plate to determine the toughness response and crack growth for the same geometries being modeled. Once experimental and simulated results were obtained, conclusions were drawn as to the abilities of the Warp3D's prediction capability.

3.8 Importance of Research

Application of the results of this study extends to other ductile materials that are well characterized for microstructure and strength properties. There are many structures that are built of ferritic steels, and steel continues to be a highly utilized structural metal. Determining the safety of structures by performing FEA is a time saving and cost saving way of assuring structural integrity. By knowing the limitation of the codes that are used

in modeling and analyzing structures, it is possible to determine when the codes may be used to accurately predict toughness and ductile crack growth, and when it is necessary to perform laboratory experiments. Furthermore, it may become feasible to analyze existing structures for toughness and crack growth where there is not sufficient experimental data to provide confidence in structural integrity, and where there is not adequate residual material that can be tested to provide this required experimental data.

The cost benefits of this approach are improvements in design efficiency and safety. By lowering failure rates of structure, there will be less repair work required and lower material costs incurred. Increased useful life of the systems can also be expected by understanding the structural response with greater accuracy.

Effective modeling also results in improved material selection by allowing designers to see how materials respond in different structures. Through better material selection, design of structures can be improved with higher confidence in structural integrity.

CHAPTER 4

RESEARCH HYPOTHESES, OBJECTIVES, AND APPROACH

4.1 Research Hypotheses and Objective

In Chapter 3, two questions were posed concerning the ductile crack growth process and its prediction of crack growth using the computational cell model. These questions translated into two hypotheses listed below:

Hypothesis 1: Experimentally, as a specimen decreases in size, the characteristic length, D , compared to its remaining crack length becomes too large to support ductile crack growth.

Hypothesis 2: In the Warp3D computational cell model, as the specimen size decreases, the element size, $D/2$, becomes too large compared to the remaining ligament and the models do not adequately predict crack growth.

Previous work had not identified a threshold to the suppression of ductile crack growth in experimental samples. All ductile materials that had been tested demonstrated ductile micro-void coalescence as the failure mode. Furthermore, in the application of the computational cell model, all of the specimen geometries that had been evaluated had demonstrated the ability to predict ductile crack growth with good accuracy. However, a limitation as to the model size was not defined. As a result, this work critically analyzed three sub-sized fracture toughness specimens (0.1 T TPB, 0.2T TPB, and 0.394TPB) experimentally and computationally to determine a threshold when the remaining

ligaments in a test sample and in a cell model become small compared to the characteristic length, D .

4.2 Approach and Area of Research

The first step was to study the previous work performed using the computational cell methodology—this was summarized in Chapter 3. For this study, it was decided to focus the research on FEA models for A516-70 as this material was fully characterized by Panontin and Nishioka and the material and material properties were readily available for utilization at the NASA Ames Research Center [10]. Panontin and Nishioka both investigated A516-70 steel and determined the characteristic length to be approximately 0.008” (200 μm). For element size modeling, it was demonstrated that the size of the element for FEA modeling was on the order of one-half the characteristic length or 0.004” (100 μm).

Experimental toughness and crack growth tests were performed on the ASTM 516-70 steel plate for three different sub-sized three point bend (TPB) specimens. The experimental approach for all of the tests is outlined and discussed in Chapter 5. The results were analyzed and J-R curves were developed for each specimen size. Results and conclusions as to the influence of specimen size are presented in Chapter 6.

After laboratory experiments, FEA models of all three small TPB geometries were analyzed using the properties of the previous work. In Chapter 7, these results are summarized and conclusions are made with respect to element size limitation for predictability of crack growth.

Once experimental and simulated results were obtained, conclusions were drawn as to Warp3D's ability to accurately predict experimental response. These conclusions are presented in Chapter 8.

4.3 Test Matrix

In this project, the largest sample tested and modeled was a three point bend specimen with Charpy-sized specimen dimensions, described by ASTM E23 for standard Charpy testing and with a notch as specified for TPB fracture toughness samples [25]. This sample was a 0.394T TPB specimen. Two additional smaller sub-sized specimens were tested and modeled. These were 0.1T TPB and 0.2T TPB specimens. Figure 13 displays two-dimensional sketches of experimental samples and Table 3 summarizes the experimental specimen matrix.

Figure 13. A schematic of the relative size scaling of TPB specimens (Not to scale).

Table 3. Experimental Test Specimen Matrix

Specimen	Number to be tested	Width, W, in. (mm)	Thickness, B, in. (mm)	Length, in. (mm)
.394T 3PB	4	0.394 (10.0)	0.394 (10.0)	2.154 (55.0)
.2T 3PB	5	0.2 (5.0)	0.2 (5.0)	1.08 (27.5)
.1T 3PB	5	0.1 (2.5)	0.1 (2.5)	1.08 (27.5)

Experimental testing was performed on ASTM 516-70 steel plate to determine the experimental J-R curves. Because of the small specimen size, single-specimen testing was difficult for the smaller two test geometries; therefore, multiple-specimen testing was used to develop the J-R curve for each geometry. In single-specimen testing, there was a requirement for unloading and loading of the specimen to be performed at incremental deflections (or incremental crack growth). Existing test procedures and equipment made this very difficult to perform and measure on the small samples. Therefore, it was easier to test a number of specimens of each size to a given load-deflection condition and to determine the associated toughness and crack growth. The actual testing is explained in greater detail in Chapter 5.

As stated in Chapter 3, the length scale associated with fracture toughness, D , was a material property and did not change in the development of FEA models. For FEA modeling, Panontin and Nishioka showed that the size of the element was on the order of one-half the characteristic length, or 0.004" (100 μ m). In this study, the results of the previous work were used to model the ASTM 516-70 steel. From the previous work review, Gao *et al.* determined that 68 was the limiting number of elements that the cell

methodology could accurately predict ductile crack growth [22]. This is shown in Table

2. The work presented in this thesis reduced the required number of elements to 42 by obtaining valid crack growth predictability results for 0.394T TPB samples. Analytically for FEA models, as the size of the specimen decreased, the number of elements decreased because $D/2$ remained constant regardless of the specimen size. Tables 3 and 4 summarize the experimental specimen sizes, the actual crack lengths, and the number of Warp3D elements in the remaining ligaments. These geometries and FEA models are explained further in Chapter 7.

Table 4. Testing Parameters for Experimental Specimens and Warp3D

Specimen	Pre-crack Length, a_0, in. (mm)	Span Width, S, in. (mm)	Specimen Width, W, in. (mm)	Warp3D Elements from crack tip to back of specimen
.394T 3PB	0.227 (5.8)	1.6 (40.6)	0.394 (10.0)	42
.2T 3PB	0.102 (2.5)	0.8 (20.3)	0.2 (5.0)	25
.1T 3PB	0.063 (1.1)	0.4 (10.2)	0.1 (2.5)	10

4.4 Experimental Analysis Techniques

The development of the experimental J-R toughness curves is critical to the understanding of the research presented in this document. There is also an additional parameter that should be introduced into this study as it was not part of the original scope. This parameter, denoted as the M-constraint parameter, is a measure of the amount of constraint as well as the amount of deformation that is accrued in a material during plastic deformation. This parameter is explained in greater detail in Section 4.4.3.

4.4.1 J-testing and Experimental Analysis Method

The J-test was originally developed by the nuclear industry for applications significantly above ambient temperatures. As a result, J-testing usually only applies to ductile fracture. During micro-void coalescence of A516-70 steel, the ductile crack growth is initially stable. This stability in crack growth allows for the quantification of ductile resistance and the development of a J-R curve.

The ASTM Standards E813 and E1152 apply when developing J-R curves. When developing the J-R curve, test specimens should be side-grooved to promote even crack growth across the fracture plane. Side-grooves help to keep high degrees of constraint in a specimen [4].

Two methods have been used to develop J-R curves. They are the multiple-specimen technique and the single-specimen technique.

4.4.1.1 Multiple-specimen J-R Curve Development

In multiple-specimen tests, a series of nominally identical specimens are loaded to select displacement levels and then unloaded. A schematic of a typical load deflection curve for one sample is shown in Figure 14. For most specimens, stable crack growth will occur during loading. After the loading and the subsequent unloading, each tested specimen is cooled by immersion in liquid nitrogen. The liquid nitrogen at -325°F

Figure 14. A schematic of a load-displacement curve for a single test specimen for the ASTM E813 multiple-specimen technique.

allows cooling into the cleavage fracture regime and completely suppresses any additional ductile crack growth. After a minimum of five minutes fully immersed, these specimen are rapidly loaded, causing brittle failure in the uncracked remaining ligament. This differentiates the ductile micro-void crack growth and the remaining ligament by introducing a ductile-cleavage line in the sample. Figure 15 shows a typical fracture surface and the location of the ductile-cleavage transition. Post test fracture surface measurements of the ductile crack are made and calculation of J from the load-deflection curve is obtained and plotted against the measured crack growth, Δa . An ideal J - R curve for a multiple-specimen test is shown in Figure 16. Each point on the curve represents one tested specimen. Seven specimens would have been tested to develop this hypothetical curve.

Figure 15. A fractograph at 375X showing a typical transition line between ductile crack growth and cleavage failure [6]. Source: Vanderbilt University (undated) [Online] Available at <http://mot.vuse.vanderbilt.edu/mse150/Fracture/Ductile> (accessed 5 February 2005).

Figure 16. An example of a J-R curve for multiple specimen testing. Point “1” represents a sample tested to a J-value of 810 lbs/in. (141.1 kN/m) with a crack growth of 0.012” (0.30 mm) and Point “2” represents a specimen tested to a J-value of 1500 lbs/in. (261.4 kN/m) and a crack growth of 0.045” (1.14 mm).

4.4.1.2 Single-Specimen J-R Curve Development

The single-specimen test technique is the most common technique because it requires far less material and produces the same information. It is also referred to as the unloading compliance method and is shown schematically in Figure 17. During incrementally equal displacements, the test specimen is partially unloaded to about 80% of the applied load, and an unloading compliance is calculated. As a crack grows in a ductile material, the specimen becomes more compliant. From the compliance measurement, it is possible to calculate a crack length using polynomial curve fit equations that are incorporated into ASTM E813 [1]. At each unloading, a J-value and a corresponding crack growth are calculated. The result is a curve similar to Figure 18.

Figure 17. A schematic of a load-displacement curve for a single-specimen technique with multiple partial unloadings.

Figure 18. An example curve for a single-specimen unloading compliance test. This curve was developed from one test specimen.

4.4.2 Use of ASTM E813 for J-R Curve Calculations

Regardless of what test method is used, a corresponding J-value needs to be calculated for each point on the J-R curve. Because ASTM E1152 does not support multiple-specimen testing, the calculation of J in this work is based on the ASTM E813 standard method. The difference between the methods is that ASTM E813 uses a fully integrated area at each unloading and calculates a new J at each unloading point. This approach incorporates the actual loading path of the load-deflection curve. ASTM E1152 calculates incremental values of J between unloadings. This method takes into account the changes in the material fracture resistance due to deformation. With multiple-specimen testing, it is not possible to calculate the J that accounts for specimen deformation because there are no multiple (interim) unloadings during the test. Since

ASTM E1152 is written specifically for single-specimen J determination, it cannot be used in this study to develop the multiple-specimen J-R curves.

Comparatively, ASTM E813 predicts slightly higher J-values at larger crack sizes. However, at small crack growth there is little deviation in calculated J for both methods since there is a relatively very small amount of change in the material at the initial stages of measurement. When determining the fracture toughness, J_{IC} , there is very little, if any, difference between the two standards since a relatively small amount of crack growth accounts for little to no difference in correction between the two methods. Furthermore, the theoretical code Warp3D uses the ASTM E813 method for reproducibility of results thus incorporating the actual loading path as well. The following section discusses the detailed method for calculation of J using ASTM E813 [1,7].

4.4.2.1 Calculation of J using ASTM E813

ASTM E813 divides J into elastic and plastic components as shown in Equation 3:

$$J_i = J_{el(i)} + J_{pl(i)} \quad \text{Equation 3}$$

The elastic portion of J is computed from elastic stress intensity, as shown in Equation 4:

$$J_{el(i)} = \frac{K_i^2 (1 - \nu^2)}{E} \quad \text{Equation 4}$$

where ν is Poisson's ratio for steel equal to 0.33 and E is the elastic modulus. $K_{(i)}$ for three point bend, TPB, specimens corresponding to a load of P_i and a displacement of δ_i is calculated in Equation 5:

$$K_{(i)} = \frac{P_i S}{(B B_N)^{0.5} W^{1.5}} f(a_0 / W) \quad \text{Equation 5}$$

where B is the specimen thickness, B_N is the net specimen thickness used for side-grooved samples, S is the span width, P_i is the load at the i th unloading, W is the specimen width, and $f(a_0/W)$ is a function dependent on the initial crack length.

The plastic portion of J , $J_{pl(i)}$ for TPB specimens, is calculated in Equation 6:

$$J_{pl(i)} = \frac{2 A_{pl(i)}}{B_N b_0} \quad \text{Equation 6}$$

where $A_{pl(i)}$ is the area under the load displacement curve at the i th unloading, and b_0 is the initial remaining ligament.

4.4.2.2 Single-specimen Determination of J

For a single-specimen with multiple unloadings, J calculations must be performed at each unloading to account for the change in the specimen crack growth. Each unloading point on the load deflection curve has an associated J and Δa . J_i , J at the i th unloading, is calculated using the total area under the curve from inception of test to the

current unloading point as demonstrated in Figure 19a and Figure 19b. This area is used in Equation 6 to calculate the plastic portion of J . As mentioned earlier, at each unloading the measured unloading compliance of the test is used to determine the corresponding crack length.

A typical resultant curve from a J-R single-specimen test is shown in Figure 20. A blunting line, with the equation $J=2\sigma_y\Delta a$, is drawn along the initial slope of the curve. This line is offset by an amount 0.006" (0.15 mm) and 0.059" (1.50 mm). The data between these two lines are used for a regression analysis to fit a curve to the data. Where the 0.008" (0.10 mm) offset line and the J-R curve intersect is known as the $J_{0.008}$ value. $J_{0.008}$ is actually J_{IC} , the fracture toughness of the material, when the specimen meets the size requirements of the standard.

None of the samples used in this study meet ASTM standard size requirements for thickness or initial ligament. According to ASTM E813, the minimum required thickness for an ASTM 516-70 steel sample to produce valid data would be 0.7" (17.8 mm) and need to have an initial ligament of 0.7" (17.8 mm). The point of this study, however, was not to meet ASTM requirements, but to predict ductile crack growth in smaller size samples. This was accomplished.

(a)

(b)

Figure 19. (a) The first curve is an example of the area that would be used to calculate J in the first unloading compliance and (b) the second curve is the example area that would be used in the i th unloading compliance measurement.

Figure 20. An example of a J-R test curve for a single-specimen multiple unloading sample.

4.4.2.3 Multiple-specimen J-R Curve

A minimum of five specimens is required to develop a multiple-specimen J-R curve resulting in five different load-deflection curves as depicted in Figure 16. Each curve is deflected to some amount δ . At this deflection, J is calculated using Equation 3. The crack growth at the deflection, δ , is measured and plotted against the corresponding J-value. A typical J-R curve for a multiple-specimen test was shown in Figure 16.

4.4.3 Material Constraint and Deformation Parameter, "M"

In the previous section, toughness was discussed in great detail. However, J is a measure of a material's resistance to crack propagation. A valid J_{IC} is defined at some

arbitrary value “close-to” crack initiation in the material. The standard method takes J_{IC} to be measured at approximately the same crack growth regardless of the specimen size. For samples whose size meets the requirements as specified in ASTM E813, this approach is valid. However, as remaining ligament and thickness are decreased, the amount of relative deformation for the same amount of crack growth in specimens of two different sizes is not the same. A smaller sample (smaller initial ligament and smaller thickness) would require more energy to create the same crack length as compared to a sample with a much larger ligament. Therefore, the smaller sample would see greater relative deformation. When discussing size constraints and size limitations in linear elastic fracture mechanics, the rule of thumb from Dodds and Gao is that “when the initial remaining ligament is 100 times the ratio of J to yield strength or $b_0 > 100J/\sigma_0$, the material is considered to have small scale yielding and the stress zone in front of the crack tip is elastically dominated” [26]. If the aforementioned size inequality is rewritten to reflect a dimensionless parameter, Equation 7 is the result:

$$\frac{b_0 \sigma_0}{J_i} > 100 \quad \text{Equation 7}$$

where b_0 is the remaining ligament, σ_0 is the nominal yield stress, and J_i is the i th J -value.

This ratio represents a non-dimensional loading level scaled to the specimen size. In ductile fracture initiation for determining J_{IC} , this ratio must be greater than or equal to 25. This is because for ductile tearing, the sensitivity to changes in small scale yielding

(SSY) is no longer as important to the determination of a toughness value. Small scale yielding variations for cleavage type failures can result in large variation in the measure of elastic toughness, and specimen size requirements are strict. In essence, the limit of 100 represents a unitless measure of the allowable deformation the sample can see before it is no longer considered a valid LEFM toughness measure. This value also provides an indication of the level of constraint in a specimen because the material would have to be highly constrained to produce such a high value. Rewriting Equation 7 by substituting an M for the integral value and setting equality, Equation 8 is obtained:

$$M = \frac{b_0 \sigma_0}{J_i} \quad \text{Equation 8}$$

where J_i represents a J -value at the i th point on the J - R curve for a specimen with an initial remaining ligament of b_0 . Regardless of the specimen size, the strength, σ_0 , is a material property and is constant. As J increases, M becomes smaller. At smaller M -values a material will experience more deformation and will have less constraint. Therefore, M is a measure of the extent of deformation, or conversely, an indication as to the loss of constraint in a specimen.

As the remaining ligament decreases, the value of J also must decrease in order to maintain a constant M -value. Essentially, in specimens of two different sizes with the same aspect ratio and at the same M -value, J is not equal. However, the relative amount of damage in the samples is the same since M is the measure of the amount of deformation.

Gao and Dodds developed a function known as $g(M)$ to indicate the level of constraint in a test specimen [27]. This function is dependent on the amount of constraint, M , as well as a material's flow properties, but is independent of the relative specimen size. Figure 21 shows an example of a constraint function of $g(M)$ versus the constraint parameter, M , for all TPB specimens down to 0.394 TPB. At the same M for all specimen sizes, they found that the constraint function was equal. At large M -values ($M > 200$), the material is highly constrained. As M decreases ($M < 200$), the material becomes more plastic and the constraint in the specimen begins to decrease. As a result, equivalent M -values indicate equivalent constraint or behavior in the material even if the specimens are of different sizes. Gao and Dodds also determined that the value of M

Figure 21. The non-dimensional constraint function, $g(M)$ for all TPB specimens with $B = W$, $S = 4W$, and $a/W = 0.5$ [27]. Source: X. Gao, C.F. Shih and R.H. Dodds Jr., "Constraint Effects on the Ductile-to-Brittle Transition Temperature of Ferritic Steels: A Weibull Stress Model," *International Journal of Fracture*, **82**, 67-95 (1996).

where constraint loss begins is highly dependent on the flow properties of the material.

For lower strength and higher strain hardening materials, higher levels of constraint are maintained at much lower values of M , as shown in Figure 22. Note that the degree of constraint decreases at lower values of M (higher degree of deformation) and smaller values of the constraint function.

Figure 22. The non-dimensional constraint function, $g(M)$ for TPB specimens with $B = W$, $S = 4W$, and $a/W = 0.5$. The material flow properties are (a) $n=10$ (n is the strain hardening coefficient), $E/\sigma_0 = 500$, and $\nu = 0.3$ (Poisson's ratio) (b) $n=5$, $E/\sigma_0 = 800$ and $\nu = 0.3$, and (c) $n=20$, $E/\sigma_0 = 300$ and $\nu = 0.3$ [27]. Source: X. Gao, C.F. Shih and R.H. Dodds Jr., "Constraint Effects on the Ductile-to-Brittle Transition Temperature of Ferritic Steels: A Weibull Stress Model," International Journal of Fracture, 82, 67-95 (1996).

It is possible to plot M versus the percent of crack growth, Δa , to the remaining ligament. Since M is a non-dimensional parameter independent of the absolute specimen size, it should be plotted against a non-dimensional parameter as well. In essence, the amount of crack growth divided by the initial remaining ligament gives a relative amount of crack growth for a given specimen at a determined M -value. An example of an expected M -curve is shown in Figure 23. For small values of crack growth to remaining ligament, M becomes extremely large. The larger the M -value, the smaller the J -value, and hence, the lower the amount of load placed on the sample, and the greater the degree of constraint.

This type of curve was developed for all the experimental geometries tested herein. The use of M was incorporated into the analysis for this work and was used to explain the loss of constraint that resulted due to size limitation in experimentation.

Figure 23. An example of an experimental M -curve plotted against relative crack growth.

CHAPTER 5

EXPERIMENTAL APPROACH AND DESIGN

The fabrication, setup, and testing of specimens are discussed in this section.

Fabrication consisted of obtaining A516-70 plate material, identifying the correct rolling and testing orientations, machining specimens, pre-cracking specimens, and testing specimens.

The experimental process was performed in the following steps:

1. Test Specimen Design
2. Materials Selection and Properties
3. Specimen Fabrication
4. Specimen Set-up
5. Specimen Pre-cracking
6. Specimen Testing and Data
7. Experimental Analysis and Results
8. Development of FEA Models and Execution of Models
9. Comparison of Experimental Results to FEA Results

5.1 Test Specimen Design

The three point bend (TPB) specimens machined and tested in this experiment were prepared according to ASTM E23, E399, E813, and E1152 standards where applicable [1,7,25,26]. A number 16 surface finish or better was obtained for all specimen faces, as required by ASTM standards. Standard milling techniques were used for extracting the 0.394T TPB specimens, however, the notches and side-grooves were cut using electrical discharge machining (EDM). The smaller 0.2T TPB and 0.1T TPB

specimens were obtained using EDM completely. Figure 24 and Figure 25 show the specimen drawings.

EDM is a very accurate method of machining, and can be used to produce very tight dimensions, especially for notch radii and sharp edges. Standard milling techniques rarely produce sharp enough starter notches to initiate fatigue cracks. When a straight starter notch is cut with a 0.003" (76 μm) diameter EDM wire, fatigue crack initiation occurs readily. In this way, using EDM to cut crack-starter notches results in shorter pre-crack times because of the sharp notch acuity.

Initially, specimens were machined with flat faces and, after pre-cracking them, 20% (10% either side) side-grooves were machined on either side of the specimens. During testing, side-grooves help to maintain plane strain conditions across the crack

Figure 24. Standard proportions for a non-side-grooved TPB specimen [26]. Source: ASTM Standard E399. "Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials." American Society for Testing and Materials, 1995.

Figure 25. Standard proportions for a side-grooved TPB specimen [26]. Source: ASTM Standard E399. "Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials." American Society for Testing and Materials, 1995.

front of a specimen [28]. Since the models in Warp3D were run in plane strain, using side-grooves to maintain this condition as best as possible was the logical approach.

5.2 Material and Material Properties

The ASTM A516-70 steel used in this study was chosen because of its use in previous studies. All data and information was readily available to perform the testing and modeling. This material is currently used in pressure vessels and in wind tunnels at

NASA Ames Research Center at Moffett Field, California. NASA Ames Research Center supported this effort.

The material and material properties of ASTM A516-70 steel that were needed to perform the experimental and computational work are summarized in Table 5 and Table 6 [10]. The chemical composition of the A516-70 steel is summarized in Table 7 [10].

Table 5. A516-70 Mechanical Properties

Material	Yield Strength ksi (MPa)	Ultimate Strength ksi (MPa)	Elongation % in 2.0" (51 mm)
A516-70	48.6 (335)	78.9 (544)	25

Table 6. A516-70 Material Properties Needed to Perform Computational Models

Property	Symbol	Value	Reference
Young's Modulus	E	30×10^6 psi (206,800 MPa)	2,10
Poisson's Ratio	ν	0.33	2,10
Initial Void Volume Fraction	f_0	0.004	10
Critical Void Volume Fraction	f_E	0.15	9
Characteristic Length	D	0.008" (200 μ m)	9

Table 7. Material Chemical Requirements for A516-70 Steel

	Chemical Composition, %					
Material	C	Mn	P	S	Si	Mo
A516-70	0.25	1.06	0.006	0.011	0.21	0.004

The material is a low-carbon manganese fine-grained steel. It is primarily used in pressure vessel steel where good notched toughness is required. The plate strength properties are characterized by minimum yield strength of 38 ksi (262 MPa) and an ultimate strength between 70-90 ksi (483-621 MPa). The minimum elongation is 21% over 2.0" (51 mm). The true stress-true strain curve is shown in Figure 26 [10].

Figure 26. True stress – true strain curve for A516-70 plate steel [10]. Source: O.S. Nishioka. 1997. Prediction and Verification of Ductile Crack Growth from Defects in Butt Welds. Master's Thesis, San Jose State University.

5.3 Specimen Fabrication

A plate of A516-70 steel measuring 5.8" x 8.4" x 0.5" (14.7 cm x 14.7 cm x 1.3 cm) was provided. The rolling direction of the steel was clearly marked for specimen extraction. Specimens in previous tests were oriented in the transverse-longitudinal (TL) orientation. This essentially means that the specimens' notches are cut parallel to the rolling direction of the steel. Typically this is the weakest toughness direction of rolled pressure vessel steel because the inclusions are aligned in the rolling direction.

Once the plate was obtained, eight 0.394" x 0.394" x 2.154" (10 mm x 10 mm x 55 mm) Charpy sized TPB specimens and eight 0.42" x 0.42" x 2.5" (10.7 mm x 10.7 mm x 63.5 mm) TPB specimens were machined using ASTM E1152 guidelines for machining test specimens. Figure 27 shows the configuration layout of the initial specimens. The larger TPB specimens were machined so that two 0.2T TPB specimens or three 0.1T TPB specimens could be extracted from the larger samples.

5.4 Test Set-up

There were two test set-ups used in these experiments. The first test set-up was used to perform the pre-cracking of all of the specimens as well as the testing of the 0.394T TPB samples. The second set-up was used to perform multiple-specimen testing on the smaller samples.

For the first set-up, the specimens were positioned on 0.4" (11 mm) rollers, separated by a 1.6" (40.6 mm) span, as shown in Figure 28. This setup was used

Figure 27. A schematic of the specimen layout for the ASTM A516-70 plate.

Figure 28. The test setup for pre-cracking all samples and for testing the 0.394T TPB specimens using the single-specimen testing technique.

for pre-cracking all of the specimens and testing the 0.394T TPB specimens. A crack opening displacement (COD) clip gage was used to determine the crack growth in each of the specimens. The COD gage was important because it allowed the experimenter to infer crack length during pre-cracking and to determine crack growth during a single-specimen multiple unloading test. As a result of using the COD, a crack length was determined for each incremental loading point for a single specimen.

The second set-up, as shown in Figure 29, was used for testing the 0.2T TPB and 0.1T TPB specimens. Span widths of 0.8" (20.3 mm) and 0.4" (10.1 mm) were used for the 0.2T TPB and 0.1T TPB specimens, respectively. A COD clip gage was

Figure 29. The test setup for toughness testing of 0.1T and 0.2T TPB specimens.

impossible to use for these small specimens, therefore, a front face deflection gage was used to measure the specimen front-face deflection. At some pre-determined displacement, the test was stopped; samples were immersed in liquid nitrogen, rapidly loaded, and fractured. The crack length was then measured for these specimens.

Multiple-specimen testing was performed using this approach.

5.5 Specimen Pre-cracking

The specimens used to determine toughness of a material are required to have very sharp cracks. These sharp cracks are obtained by a fatigue cycling process known as

pre-cracking. The smaller the specimens, the more difficult it is to control the parameters for pre-cracking.

Because of the difficulty in pre-cracking small specimens, especially the 0.1T TPB and 0.2T TPB specimens, the 0.42T TPB specimens were machined and pre-cracked to the desired lengths. Once the pre-cracking was performed to the desired length, the 0.2T TPB and 0.1T TPB samples were machined from the larger samples. A simple schematic outlining the sample extraction steps is shown in Figure 30. The same process was used to extract the 0.1T TPB and the 0.2T TPB samples. All post-machining of specimens included a 20% side-groove.

Figure 30. A schematic of the sample extraction from a 0.42T TPB specimen.

Since the smaller samples were extracted from the 0.42T TPB sized specimens, the pre-crack properties for establishing the proper a/W ratios were used according to ASTM E1152, as shown in Table 8 [7]. The minimum pre-crack required for these specimens was 50 mils (1.3 mm) of pre-crack growth. Each sub-sized sample was post machined to attempt to finish with a/W equal to 0.5. This was a difficult task to accomplish due to the inability of understanding exactly where the pre-cracks were.

Table 8. Pre-crack Parameters for Testing Experimental Specimens

Spec.	Crack Length to Width Ratio, a/W	Stress Intensity Factor, ΔK , ksi $\sqrt{\text{in.}}$ (MPa $\sqrt{\text{m}}$)	Max Stress Intensity, K_{max} , Ksi $\sqrt{\text{in.}}$ (MPa $\sqrt{\text{m}}$)	Pre-crack Max Load, P, lbs (N)	Min to Max Pre-crack Ratio, R
.394T TPB	0.5	11.0 (12.1)	13.3 (14.6)	196 (872)	0.1
0.42T TPB	0.5	11.5 (12.7)	13.9 (15.3)	240 (1068)	0.1

A 3,000 pound load cell mounted into a 20,000 pound load frame with an MTS electro-hydraulic servo-controlled actuator was used for fatigue pre-cracking and testing. Pre-cracking was performed in load control with a constant cyclic load. The load was adjusted as the crack grew to assure that the specimens never exceeded the 11.0 ksi-in^{0.5} (12.1 MPa-m^{0.5}) stress intensity factor as defined in ASTM E1152 and shown in Table 8.

In load control, the maximum load is never allowed to exceed at least one-half of the limit load, P_{LL} . The limit load is defined as the load at which a beam in simple

bending will yield. The equations used to calculate the limit load and maximum allowable pre-crack load for a given TPB geometry are shown in Equations 9 and 10:

$$P_{LL} = \frac{4B_e b_0^2 \sigma_y}{3S} \quad \text{Equation 9}$$

$$P_{max} = 0.5P_{LL} \quad \text{Equation 10}$$

where B_e is the effective thickness, b_0 is the remaining ligament, σ_y is the yield strength, and S is the span width of the specimen. P_{max} is the maximum allowable load during pre-cracking.

For the specimens pre-cracked in this study, the pre-crack loads never exceeded the value of P_{max} . To further reduce the amount of potential plasticity that could develop at the crack tip, the last 25 mils (0.64 mm) of the pre-crack were cracked at loads 0.4 times the limit load or at a stress intensity that did not exceed $9 \text{ ksi-in}^{0.5}$ ($9.9 \text{ MPa-m}^{0.5}$), whichever was smaller.

The MTS system software allowed for a calculated pre-crack based on the compliance measurement obtained via the COD clip gage. In addition, visual observations of the cracks were made throughout all of the pre-cracking. A scribe was used to mark the location of the final pre-crack and a thin layer of oil was dripped into the notch in order to give a clear visual location of the crack. This method was not always successful due to lighting and reflection from the specimens' surfaces. This was evidenced by pre-cracks longer than desired in the 0.394T and 0.1T TPB specimens.

Once the desired crack lengths were achieved, the 0.394T TPB specimens were side-grooved and tested. The 0.42T TPB specimens were machined into the smaller 0.1T TPB and 0.2T TPB specimens as described earlier and shown in Figure 30. Side-grooving was performed after pre-cracking because it was much easier to observe crack growth without side-grooves present on the specimen. Figure 25 shows a sketch of specimen side-grooving; Figure 31 shows a photo of an actual 0.2T TPB sample with a side-groove.

5.6 Specimen Testing

As discussed in Section 4.4.2.2, the 0.394T TPB samples were tested using the single-specimen test technique. This sample size allowed for the use of a COD clip gage, as shown in Figure 28, to measure compliance. As a result, the crack growth was measured as the test was performed. The tests were run in COD control. This means that

Figure 31. A post machine photograph of a pre-cracked side-grooved sample.

at each 2 mils (0.05 mm) of COD displacement, the samples were unloaded to 20% of the applied load and then reloaded, a compliance measurement was taken, and a crack length was calculated based on ASTM E813 inference equations [1].

Crack length calculations were performed automatically by MTS software, thus eliminating the potential for calculation error. The physical test set-up shown in Figure 28 was used to perform these tests.

There were a total of four tests run for the 0.394T TPB specimens. Each sample was run to a different crack length in order to assure that the FEA model predictions duplicated the experimental results for the J-integral value at that specific crack growth.

The 0.1T TPB specimens and the 0.2T TPB specimens were tested using the multiple-specimen test technique as described in Section 4.4.1.1. A total of seven samples were tested for each curve using the setup shown in Figure 29. Data from two samples in each set were not valid due to test run errors. The smaller samples were very difficult to position, to align, and to preload properly. The two 0.1T TPB samples were lost due to pre-test overloading of the samples, and the two 0.2T TPB samples were lost due to misalignment of both the displacement gage and the load cell on the specimens. However, sufficient data were collected to construct the J-R curves.

CHAPTER 6

EXPERIMENTAL RESULTS

This chapter presents the experimental results. The load deflection for each size sample is presented in Section 6.1. The toughness versus crack length, J-R, curves are discussed in Section 6.2, and the M-constraint curves are discussed in 6.3.

6.1 Load Deflection Curves

The experimental load deformation curves are summarized in the following sections.

6.1.1 Load-Deflection for 0.394T TPB Samples

The load-deflection, $P-\delta$, curves for the 0.394T TPB samples are shown in Figure 32. The sample curve for the CVN2 specimen fell significantly below the others. Post test fracture surface examination revealed a pre-crack length that resulted in an $a/W=0.6$. Samples CVN3 and CVN5 had pre-crack lengths corresponding to $a/W=0.58$, and Sample CVN6 had a pre-crack length corresponding to an $a/W=0.57$. Although the a/W values were within close agreement, increases in initial crack length resulted in decreases in remaining cross-sectional area for each specimen. As the cross-sectional area or remaining ligament decreased, the specimen required less energy to propagate a

Figure 32. Load-deflection curves for 0.394T TPB specimens.

crack; therefore, the $P-\delta$ curves had smaller maximum peak loads at the same amount of deflection compared to specimens with larger crack lengths. Table 9 summarizes the post test information.

Table 9. Data Summary for 0.394T TPB Samples

Specimen	Maximum Deflection Test, δ , in. (mm)	a/W	Initial Crack Length, a_0 , in. (mm)	Final Crack Length, a_f , in. (mm)	Total Crack Growth, Δa , in. (mm)	Toughness, $J_{0.008}$, lbs/in. (kN/m)
CVN2	0.036 (0.91)	0.60	0.237 (6.02)	0.254 (6.45)	0.017 (0.43)	1203 (209.5)
CVN3	0.026 (0.66)	0.58	0.229 (5.82)	0.241 (6.12)	0.012 (0.30)	-----*
CVN5	0.060 (1.52)	0.58	0.229 (5.82)	0.250 (6.35)	0.021 (0.53)	1197 (208.5)
CVN6	0.103 (2.62)	0.57	0.226 (5.74)	0.294 (7.47)	0.068 (1.73)	1200 (209.1)

* - This sample was not tested to a crack growth capable of measuring $J_{0.008}$.

Normalized P- δ curves were established for better comparison of the data.

Essentially, normalizing the curves removed the geometry dependency on the load deflection. If the applied load, P_a , for each sample is normalized with respect to the calculated limit load, P_{LL} , as shown in Table 10, and the corresponding deflection, δ , is normalized to the remaining ligament, b_0 , the curves should be very close to one another. The P_{LL} took into consideration the effective thickness, B_e , of the sample as well as the remaining ligament, b_0 . Once P_a was normalized to the corresponding P_{LL} , the corresponding ratio took out the variability due to B_e and b_0 . Each P- δ curve was normalized to each measured b_0 as shown in Figure 33.

Table 10. Remaining Ligament and Limit Load, P_{LL} , for Each 0.394T TPB Sample

Specimen	a/W	Remaining Ligament, b_0 , in. (mm)	Limit Load, P_{LL} , lbs (N)
CVN2	0.60	0.157 (3.99)	242.4 (1076)
CVN3	0.58	0.165 (4.19)	267.7 (1191)
CVN5	0.58	0.165 (4.19)	267.7 (1191)
CVN6	0.57	0.169 (4.29)	277.5 (1234)

B_e for the 20% side-grooved CVN sample was calculated to be 0.378" (9.6 mm). The remaining ligament, b_0 , was determined by subtracting the initial crack length, a_0 , of each sample from the sample thickness, W , of 0.394" (10 mm). As shown in the normalized curves of Figure 33, the results agreed very well.

Figure 33. Normalized load-deflection curve for 0.394T TPB specimens.

6.1.2 Load-Deflection for 0.2T TPB Samples

Figure 34 displays the P - δ curves for the 0.2T TPB samples. As established for the 0.394T TPB specimens, as b_0 decreased, P - δ curves showed decreases in peak load capability for a given sample. Markers and arrows were used to identify each of the curves corresponding to a given specimen. P - δ curves were normalized in Figure 35 to see how well the data agreed—the agreement was remarkably good. Table 11 summarizes the data for the 0.2T TPB specimens, and Table 12 summarizes the data needed for the normalized curves.

Table 11. Data Summary for 0.2T TPB Samples

Specimen	Maximum Deflection, δ , in. (mm)	a/W	Initial Crack Length, a_i , in. (mm)	Final Crack Length, a_f , in. (mm)	Total Crack Growth, Δa , in. (mm)
H1	0.064 (1.63)	0.49	.098 (2.49)	0.106 (6.45)	0.063 (1.60)
H2	0.016 (0.41)	0.54	0.108 (2.74)	0.112 (6.12)	0.004 (0.10)
H3	0.030 (0.76)	0.54	0.108 (2.74)	0.120 (6.35)	0.012 (0.30)
H4	0.035 (0.89)	0.51	0.102 (2.59)	0.123 (7.47)	0.021 (0.53)
H5	0.024 (0.61)	0.50	0.100 (2.54)	0.272 (6.91)	0.007 (0.18)

Figure 34. Load-deflection curves for the 0.2T TPB specimens.

Table 12. Remaining Ligament and Limit Load, P_{LL} , for Each 0.2T TPB Sample

Specimen	a/W	Remaining Ligament, b_0 , in. (mm)	Limit Load, P_{LL} , lbs (N)
H1	0.49	0.102 (2.59)	115.9 (516)
H2	0.54	0.092 (2.34)	98.4 (438)
H3	0.54	0.092 (2.34)	98.4 (438)
H4	0.51	0.098 (2.49)	107.0 (476)
H5	0.50	0.100 (2.54)	111.4 (496)

Figure 35. Normalized load-deflection curve for the 0.2T TPB specimens.

The effective thickness, B_e , for all of the 0.2T TPB samples was calculated to be 0.198" (5.02 mm). Post test measurements confirmed this to be accurate.

6.1.3 Load-Deflection for 0.1T TPB

As specimen size decreased, small changes in b_0 had dramatic effects on the P- δ curves. Any small change in a dimension resulted in large effects on the output. One mil difference in crack length could have resulted in a 5% change in a calculated limit load. This would have translated to a 5% error in normalized curves. Machining tolerance became very important as well. B_e could have dramatically affected the limit load for a specimen.

For 0.1T TPB samples, B_e and b_0 were measured with great care so that scatter in data results was minimized. Large errors in measurements could have easily resulted in large errors in normalized curves. Therefore, the 0.1T TPB samples were loaded into a scanning electron microscope (SEM) and fractography images were taken in order to get the maximum magnification while maintaining focus and accurate dimensions. Figure 36 is an image of the first 0.1T TPB post test fracture. There was no crack growth for this sample.

Table 13 and Table 14 summarize the data for the 0.1T TPB tests. Table 13 summarizes the deflection and crack characteristics of the sample, while Table 14 summarizes the limit load information. The net thickness, B_N , of SML2 was around 0.070" (1.78 mm), resulting in an effective thickness of 0.091" (2.31 mm). If an assumed B_N of 0.08" (2.03 mm) had been used as specified for a 20% side-groove, the error in P_{LL}

Figure 36. An SEM image of a 0.1T TPB fracture surface with no crack growth.

Table 13. Data Summary for 0.1T TPB Samples

Specimen	Maximum Deflection, δ , in. (mm)	a/W	Initial Crack Length, a_i , in. (mm)	Final Crack Length, a_f , in. (mm)	Total Crack Growth, Δa , in. (mm)
SML1	0.050 (1.27)	0.65	0.065 (1.65)	0.091 (2.31)	.026 (0.66)
SML2	0.030 (0.76)	0.63	0.063 (1.60)	0.080 (2.03)	.017 (0.43)
SML3	0.012 (0.30)	0.62	0.062 (1.57)	0.062 (1.57)	0 (0)
SML4	0.019 (0.48)	0.63	0.063 (1.60)	0.070 (1.78)	0.007 (0.18)
SML5	0.024 (0.61)	0.62	0.062 (1.57)	0.073 (1.85)	0.011 (0.28)

Table 14. Remaining Ligament and Limit Load for Each 0.1T TPB Sample

Specimen	a/W	Remaining Ligament, b_0 , in. (mm)	Net Thickness, B_N , in. (mm)	Effective Thickness, B_e , in. (mm)	Limit Load, P_{LL} , lbs (N)
SML1	0.65	0.035 (0.89)	0.076 (1.93)	0.094 (2.39)	15.4 (68.5)
SML2	0.63	0.037 (0.94)	0.070 (1.78)	0.091 (2.31)	15.6 (69.4)
SML3	0.62	0.038 (0.97)	0.078 (1.98)	0.095 (2.41)	14.0 (62.3)
SML4	0.63	0.037 (0.94)	0.080 (2.03)	0.096 (2.44)	15.6 (69.4)
SML5	0.62	0.038 (0.97)	0.080 (2.03)	0.096 (2.44)	13.9 (61.8)

would have been 5.5%. This error would have translated to the normalized P- δ curves.

Figure 37 and Figure 38 show the P- δ and the normalized P- δ curves, respectively.

The normalized curves show excellent agreement with one another. There is more scatter in the 0.1T TPB curves than the 0.2T TPB and 0.394T TPB curves. As specimen size decreases, measurement errors contribute more and more to the actual resultant curves. This was observed in the smallest samples in this work.

6.1.4 Comparison of the Load-Deflection Curves

Figure 39 shows the average normalized P- δ for all three specimen sizes. The different test curves for each size were overlaid, and an average curve was obtained to see if any information on the different specimen geometries emerged. When normalized, since the geometry configurations were all the same, the curves should have overlaid well, especially in the elastic portion of the curve. In Figure 39, 0.394T TPB samples and

Figure 37. Load-deflection curves for 0.1T TPB specimens.

Figure 38. Normalized load-deflection curves for 0.1T TPB specimens.

Figure 39. Average normalized P- δ curves for all three sizes of specimens.

0.2T TPB samples agreed very well, but the 0.1T TPB samples had a shallower slope than the other geometries. This slope variation was attributed to measurement errors in the data. The linear measurement deviation for each specimen size was the same; however, the error increased by a factor of 2 from the 0.1T TPB to the 0.2T TPB dimensions and a factor of 4 from the 0.1T TPB to 0.394T TPB dimensions.

In addition, the curves overlaid very well up to a ratio of 0.20 δ/b_0 . Separation of the curves beyond this was most likely due to a variation of the loss of constraint as a function of crack length in the specimen.

6.2 Determination of J-R Curves

The J-R curves for the experimental specimens are summarized in the following section.

6.2.1 J-R Curves for 0.394T TPB Specimens

After completion of the test results, the multiple unloading determinations of J was used to develop J-R curves for the 0.394T TPB samples. The calculation and determination of J-R curves for multiple unloading were previously discussed in Chapter 4. The resultant J-R curves for the four CVN samples are shown in Figure 40. All of the curves are in fairly good agreement with one another. Three of the four specimens

Figure 40. J-R curves for the 0.394T TPB specimens.

yielded $J_{0.008}$ values in accordance with ASTM 1152 [7]. Table 15 summarizes $J_{0.008}$ values for the 0.394T TPB specimens. Specimen CVN3 did not have enough crack growth to determine $J_{0.008}$ values. The 0.394T TPB value of J agreed well with the previous J_{IC} values associated with this material of 1210 lbs/in. (210.8 kN/m) [12]. The $J_{0.008}$ value for the 0.394T samples was approximately 1200 lbs/in. (209.1 kN/m) and was associated with 0.008" (200 μ m) of crack growth. The CVN6 sample had crack growth beyond the capability of the test equipment clip gage. Beyond 0.04" (1 mm) of crack growth, the specimen no longer showed repeatable and accurate prediction of crack growth. This occurred beyond the point where $J_{0.008}$ was determined and did not influence the determination of $J_{0.008}$.

Table 15. $J_{0.008}$ Data Summary for the 0.394T TPB Samples

Specimen	a/W	Total Crack Growth, Δa , in. (mm)	Toughness, $J_{0.008}$, lbs/in. (kN/m)
CVN2	0.60	0.017 (0.43)	1203 (209.3)
CVN3	0.58	0.012 (0.30)	----*
CVN5	0.58	0.021 (0.53)	1197 (208.6)
CVN6	0.57	0.068 (1.73)	1200 (209.1)

* - $J_{0.008}$ could not be measured for this sample.

6.2.2 J-R Curves for 0.1T and 0.2T TPB Specimens

J-R curves for the 0.1T TPB and 0.2T TPB samples were determined using multiple-specimen testing. The $J_{0.008}$ values for the 0.2T and the 0.1T samples were summarized in Table 16. Each point on the J-R curves represents a different sample. Figure 41 and Figure 42 show J-R curves for the 0.2T TPB and 0.1T TPB samples, respectively. Curve fits were performed on the data to determine the $J_{0.008}$ values.

Table 16. $J_{0.008}$ Values for the 0.1T and 0.2T TPB

Specimen Size	$J_{0.008}$ lbs/in. (kN/m)
0.1 T	626 (109.1)
0.2T	783 (136.4)

Figure 41. J-R curve for the 0.2 TPB specimens.

Figure 42. J-R curve for the 0.1 TPB specimens.

The curve fits were performed on the linear portions of the curves that extended further than the 0.006\" (150 μm) exclusion line.

6.2.3 Comparison of the $J_{0.008}$ Values for Different Specimen Sizes

As the specimen size decreased, the $J_{0.008}$ values for each specimen decreased as well. This is opposite of what is typically reported in the literature. Usually as specimen size decreases, the loss in constraint at the sides of the specimen results in increased J-values because plane stress conditions dominate, thus resulting in maximum toughness. However, as a specimen becomes smaller and smaller, at some point the actual volume of the material is not capable of absorbing the plastic deformation energy; therefore, the

material toughness decreases, as shown in Figure 43. This was the reason that $J_{0.008}$ decreased with decreasing thickness in this experiment.

6.3 Determination of M-constraint or Relative Damage

Initial assessment of the J-R curves would have led to a valid conclusion that the 0.2T TPB samples and the 0.1T TPB samples were not capable of yielding a $J_{0.008}$ value equal to that of the larger samples; therefore, the TPB specimen size capable of producing $J_{0.008}$ at the same value as the larger samples would have fallen between the 0.394T TPB and 0.2T TPB samples. Comparison of the previous 1T CT resultant $J_{0.008}$ of 1210 lbs/in. (210.8 kN/m) to the 0.394 T TPB sample with $J_{0.008}$ equal to 1200 lbs/in. (209.1 kN/m) showed good agreement. The two $J_{0.008}$ values were within 1.6% of one

Figure 43. Variation in toughness with sample thickness [29]. Source: R.W. Hertzberg, Deformation and Fracture Mechanics of Engineering Materials, 3rd ed. (John Wiley and Sons, Inc., New York, 1989), pp. 295-297.

another. From sample set to sample set, J can have as much as 10% in error for measured J for the same sample size [4]. The ability to measure equal J -integral values at the same amount of crack growth in the 0.394T TPB and the 0.2T TPB had changed. For equal J -values, the amount of crack growth was different.

However, this conclusion did not give justification to say that the samples no longer were behaving the same in terms of constraint and crack growth; it shows that they were not able to give a valid J_{IC} value. For specimens that yielded the same J_{IC} or $J_{0.008}$ value, the value of M at that location on the J - R curve was not equal. Essentially J_{IC} was good to use as an indication of fracture resistance for thick materials but not for thinner materials. J_{IC} was not measured at the same level of deformation for any specimens of different sizes. A change had occurred for measuring J between the 0.394T TPB and the 0.2T TPB, but it could not be concluded that the specimens were behaving differently with respect to constraint loss.

6.3.1 Plotted M -curves

Determination of the $J_{0.008}$ value corresponds to the same amount of crack growth in any size specimen that meets the constraint criteria of having an M -value equal to or greater than 25. However, in two different sized specimen of the same relative geometry that produce the same $J_{0.008}$ value at the same amount of crack growth, the M -value is not equal since the remaining crack ligament is different and M is dependent on the remaining ligament length. In essence, J is not an indication of the amount of

deformation in the specimen. J is the amount of energy per unit area that is required to grow the crack in that sample. Deformation represents a concept of relative uniformity of damage in the sample as well as a level of constraint. Two specimens with the same M -constraint value have the same percentage of damage.

The M -constraint value was calculated at the J -integral values in the J - R curves and plotted against the amount of crack growth to initial remaining ligament. From Section 4.4.3, the M curves were derived from the measured J - R curves. Once derived, the M curves for all three sample sizes were overlaid for comparison. These curves are shown in Figure 44.

6.3.2 Discussion of M -curves

In Figure 44, it is shown that for an M -value in the range of 5.5 to 6.5 the amount of crack growth per unit length of the remaining ligament was equivalent. Using the argument presented by Gao and Dodds that at equal M -values the constraint is equal for different sized samples, the range where M versus crack growth per unit length of the remaining ligament occurred at the same constraint and deformation levels for the 0.394T TPB and 0.2T TPB specimens [27]. However, this argument did not hold for the 0.1T TPB specimens. The level of constraint in the 0.1T TPB was different from the other two sizes for all measured values of M . However, ductile crack growth was still occurring in the smaller samples. Ductile crack growth was not suppressed completely in the 0.1T TPB samples; therefore, the experimental threshold for suppression of ductile cracking was not reached.

Figure 44. M versus relative crack growth for 0.1T, 0.2T, and 0.394 TPB specimens.

For TPB specimens between 0.2T and 0.394T thickness, in the range of $M=5.5$ to 6.5, M could be used to predict the amount of crack growth in the A516-70 TPB specimens. However, prior to $M=6.5$, the relative amount of crack growth was not equivalent for the same M -value. There was a significant amount of error in the measurement of M and crack growth for the smaller samples. The error bars associated with these measurements are shown in Figure 44. Even with the error bars, the 0.1T TPB sample did not overlap with the larger two configurations. It was fair to conclude that the 0.1T TPB sample did not behave or did not experience the same conditions as the 0.2T and 0.394T TPB specimens at any point during the experimental testing. However, there was evidence to propose that for the same amount of relative crack growth, the 0.2T and 0.394T TPB specimens produced the same amount of relative deformation for M in the

range of 5.5 to 6.5. Table 17 summarizes M-values at the same amount of relative crack growth for all three samples. The 0.2T TPB and 0.394T TPB curves showed very good agreement.

Table 17. Comparison of M-values for Relative Values of Crack Growth

Relative Crack Growth $\Delta a/b_0$	M for 0.394T TPB	M for 0.2T TPB	M for 0.1T TPB
0.1	6.2	6.2	5.6
0.2	5.6	5.6	4.1
0.3	5.0	4.9	3.2

Table 18 summarizes data for two specimens of different sizes with similar amounts of relative crack growth. Two different sized bend bars of different configurations were compared at the same amount of relative crack growth.

Table 18. Comparison of Two Specimens with The Same M-value

Sample #	Sample Size TPB	Relative Deflection, $\Delta a/b_0$	Toughness, J, lbs/in. (kN/m)	Remaining Ligament, b_0 , in. (mm)	M	Crack Growth, Δa , mils (mm)
H3	0.2T	0.12	620 (108.0)	0.102 (2.59)	5.65	12 (0.30)
CVN2	0.394T	0.12	1200 (209.1)	0.157 (3.99)	5.80	17 (0.43)

The relative amounts of deformation appeared similar on the fracture surface of the samples. Table 19 showed a comparison for the 0.2T TPB sample, H3, and 0.394T TPB samples, CVN2 which have comparable M-values at the same amount of relative crack growth. The crack growth fracture surfaces of these two samples were compared, as shown in Figure 45, and approximately the same amount of relative damage was observed in the samples.

Figure 45. Comparison of a 0.2T TPB specimen and a 0.394 TPB specimens' ductile crack growth (shown between the two white lines) fracture surface with approximately the same M-values of 5.65 and 5.80, respectively. There is about the same amount of relative damage for both samples, and it is seen as ductile micro-void coalescence.

CHAPTER 7

FINITE ELEMENT MODELING AND RESULTS

In this research, the computational cell methodology was challenged in its ability to predict toughness and crack growth in small specimens of A516-70 steel. Application of the method required that the stress-strain response of the material was known. In addition, the element size in the models was a constant dictated by the material. Nishioka and Panontin demonstrated the capability of the computational cell methodology to predict crack growth in 1T CT samples of A516-70 steel as shown in Table 1 [10]. A code that was developed at the University of Illinois known as Warp3D was used to run the computational cell models [8]. This code is an analysis code that can be run on an IBM compatible computer platform. In this study, a DELL Precision 330 with a 1.6 MHz coprocessor with 512 MB of RAM was used.

7.1 Warp3D Finite Element Software and Modeling

To describe a given structure or specimen, Warp3D only supports the use of an 8-node isoparametric element known as “l3disop”, shown in Figure 46. This is a

Figure 46. An illustration of an 8-node isoparametric element needed to describe a structure in Warp3D.

three-dimensional (3-D) element; and therefore, two-dimensional (2-D) models are represented as thin three-dimensional components with boundary conditions placed on the two out-of-plane surfaces.

All the experiments in this research were performed under quasi-static loading conditions. As a result, all FEA models were loaded in displacement control, which means that forced displacements were applied at nodes that represented loading places on the specimen. The placement of the loading for the models was the same as the placement on experimental samples. Incremental displacement of the nodes was selected to make sure that the specimen was not displaced in steps too large so as to decrease the accuracy of the code predictions.

The computational cell methodology, or the G-T method discussed in Chapter 3, was used to represent ductile crack growth. With this approach the amount of yield

surface grew with increased strain hardening of the material, but the yield surface decreased as the void volume fraction increased. At a void volume fraction of 0.1 for an element, the element stiffness decreased until the critical void fraction of 0.15 was reached. At this point, the element was considered failed or “killed” and the load carrying capacity of the element became zero. This means that the element was no longer incorporated in the determination of the stress-strain analysis. A “killed” element represented crack growth; therefore, the element acted like a free surface.

The models that were run for this research in Warp3D were compiled in P8/PATRAN, a geometric, pre- and post-processor manufactured by the MacNeal Schwendler (MSC) Company Ltd. Models were output from PATRAN as independent or neutral platform files and then converted to Warp3D compatible files using a conversion program known as Patwarp. Results were then post processed using text file outputs from Warp3D.

7.2 Material Property Inputs for Models

There were a number of parameters that were needed for Warp3D to obtain accurate results. Since this study was based on work performed by Nishioka and Panontin, the same parameters used in their study were used in this work [10].

7.2.1 Mechanical Properties

The basic mechanical properties of the material that were needed to perform the modeling and analysis in FEA are displayed in Tables 6 and 7. Nishioka and Panontin

measured and determined the stress-strain curve for the A516-70 steel, shown in Figure 26, and this curve was used in the models.

7.2.2 Element Size and Characteristic Length

The element size to characteristic length relationship is described in Chapter 3. For A516-70 plate, Nishioka and Panontin determined the element size to be 0.004" (100 μm), or one-half of the characteristic length [10].

7.2.3 Parameters Used in Previous Work

To assure that this work did not change any previous parameters, Table 19 was constructed from previous work and these values were used in all of the models run in this research. Recall that the previous work demonstrated the effective use of these values in modeling crack growth in larger 1T CT samples. These values were calibrated and verified by previous work and applied in this work on much smaller samples [10].

Table 19. Warp3D Input Parameters

Property	Symbol	Value	Units
Young's Modulus	E	30000 (207000)	ksi (MPa)
Poisson's Ratio	ν	0.3	
Initial Void Fraction	f_0	0.004	
Maximum Void Fraction before Crack Propagates	F_E	0.15	
Stress- Strain Curve		Piecewise Linear	
Element Cell-Size	D	0.004 (200)	inch (μm)

7.3 Two-Dimensional Modeling

Once the necessary Warp3D input parameters were determined and the laboratory experimental data were summarized, FEA models of the three test specimen geometries were developed in PATRAN. These models were run to determine how well Warp3D predicted actual experimental data in plane strain condition and to determine at what point the element size became too large for accurate theoretical output.

There were three geometries experimentally tested; 0.394T TPB, 0.2T TPB, and 0.1T TPB specimens. The results of these tests are summarized in Chapter 6. The smallest sample modeled was a 0.1T TPB sample with an average initial crack, a_i , of 0.063" (1.6 mm). This gave an average a/W ratio equal to 0.63 for these samples. Table 13 shows the 0.1T TPB experimental summary. The second sample modeled was a 0.2T TPB sample with an initial average crack length of 0.102" (2.6 mm) and an average a/W ratio of 0.51, described in Table 11. The largest sample modeled was a Charpy sized 0.394T TPB specimen with an average initial crack of 0.227" (5.7 mm), and an average a/W of 0.58. Table 9 summarizes the experimental data for the 0.394T TPB specimens.

The three specimen sizes resulted in different numbers of elements across the remaining ligament for each model. The element size, $D/2=0.004$ " (100 μm), was a constant for all models. For 0.394T TPB specimens with an $a/W=0.58$, the number of elements in the remaining ligament was 42. As specimen dimensions were reduced, so were the number of remaining elements along the ligament such that a 0.2T TPB specimen with an $a/W=0.51$ had only 25 remaining elements. The 0.1T TPB sample model with an $a/W=0.63$ had 10 elements in the remaining ligament. The crack plane

element size is the same for all geometries since the element size of 0.004" (100 μm) is a material property linked to the characteristic length. Once the element size was determined, it was fixed and was independent of geometry, as shown in Figure 47. Table 2 summarizes the information for the Warp3D geometry model conditions.

Figure 47. FEA 2-D crack front models showing constant element size and decreasing number of elements as model size decreases.

To reiterate, a Warp3D two-dimensional analysis is different from a standard two-dimensional analysis. This difference is based on the fact that Warp3D uses 8 node isoparametric brick elements, thereby requiring that all models have a thickness component. For this work, the thickness component was specified in PATRAN and transferred to Warp3D input files. As a result, along with the displacement control and application of constraint at the bend locations, out-of-plane constraint was needed and placed on the front and back face of every element. Since out-of-plane motion (strain) was prohibited, the analysis became one of plane strain. Regardless of the specified thickness, for the same two-dimensional geometry, the models predicted the same J-R curve because the theoretical model ran entirely in plane strain condition. However, the Warp3D load prediction output of the model changed with the specified thickness. Therefore, it was necessary to use the equivalent thickness, B_e , of the laboratory samples in order to get the same load-deflection response from Warp3D.

7.4 Warp3D J-R Curves Compared to Experimental Results

The results of the two-dimensional analysis for all three sizes were compiled and compared to the experimental results obtained in the laboratory. All models were run to the maximum experimental deflection. Toughness versus crack length and the load deflection curves were summarized from the Warp3D results. The Warp3D results were overlaid onto the experimental data plots as shown in Figure 48 through Figure 53.

Figure 48. J-R curves, including Warp3D results, for the 0.394T specimen with an $a/W=0.58$.

Figure 49. J-R curves for the 0.2T TPB specimen with an $a/W=0.51$. Warp3D results are shown.

Figure 50. J-R curves for the 0.1T TPB specimen with an $a/W=0.63$. Warp3D results are shown.

Figure 51. Normalized load-deflection curves with Warp3D results for 0.394T TPB specimens.

Figure 52. Normalized load-deflection curve with Warp3D results or 0.2T TPB specimens.

Figure 53. Normalized load-deflection curve with Warp3D results for 0.1T TPB specimens.

It is evident from Figure 48 and Figure 51 that the 0.394T TPB specimens' experimental results showed excellent agreement with Warp3D theoretical predictions. In Figure 49, the 0.2T TPB J-R curves agreed up to approximately 0.004" (100 μ m) of crack growth and a J-value of 480 lbs/in. (83.6 kN/m). Beyond these values, there was no agreement. Load-deflection data for the 0.2T TPB samples is shown in Figure 52 and was in agreement up to experimental peak loads. Beyond peak loads, constraint loss was observed in the experimental data resulting in deviation between the theoretical and experimental curves. This overlay agreement corresponded to an approximate δ/b_0 value of 0.2, which corresponded to about 0.019" (475 μ m) of theoretical deflection and 0.004" (100 μ m) of crack growth. As shown in Table 11 for sample H2 experimental results, there was 0.016" (400 μ m) of deflection and 0.004" (100 μ m) of crack growth for the 0.2T TPB sample. This was in close agreement with the theoretical model.

A similar load-deflection effect occurred in the 0.1T TPB samples shown in Figure 52. Agreement up to δ/b_0 of about 0.3 was seen. This agreement corresponded to 0.011" (275 μ m) of theoretical deflection and no crack growth. From Table 13, experimentally at 0.012" (300 μ m) of deflection, no crack growth was observed. For the 0.1T TPB samples, the theoretical and experimental J-R curves showed no agreement for crack growth prediction. Warp3D using A516 plate steel properties, a 0.1T TPB 2-D model, a 0.004" (100 μ m) element size, and plane strain conditions could not be used to predict crack growth.

7.5 FEA Mesh Effects

One of the questions posed in this study is: When does the element size become too large relative to the remaining ligament? In this study, there were three geometries modeled. All had the same crack front element size of 0.004" (100 μm). As specimen size decreased, the total number of elements across the remaining ligament decreased, therefore, the ratio of remaining ligament to element size decreased.

For a 0.394T TPB specimen with $a/W=0.58$, the remaining ligament was 0.167" (4.2 mm), and the ratio of remaining ligament to element size was 42. For the 0.1T TPB specimen with an $a/W=0.63$, the ratio of remaining ligament to element size was 10 which was 4 times smaller than the 0.394T sample. Because of the constraint imposed on the models, it was difficult to conclude that mesh effects alone caused the inability to predict experimental J-R curves. Additional work was performed to resolve the question.

7.5.1 Warp3D Crack Tip Normalized Stress Profile

As forced displacement is applied at the back of a specimen or in a model, a stress profile along the crack front begins to develop from the crack tip to the back of the specimen. For ductile materials, the crack tip goes through a blunting process and at some finite distance, R , in front of the crack, the stress becomes significantly high (3-4 times greater than the nominal yield) such that this stress causes void growth and coalescence, which eventually results in crack front propagation. Provided the samples have the same constraint and the exact geometric configuration (same a/W , W/B , and S/W ratios), it is possible to normalize the stress profile. At the same level of

deformation and constraint, normalized stress profiles should be the same for all geometries. In Warp3D, since plane strain is imposed on the FEA models, any deviation from this normalized stress profile would indicate where mesh effects are causing error in the output.

To further explain this effect, the use of non-dimensional constraint variable, M , (discussed in Section 4.4) was employed. Gao and Dodds utilized this M parameter in discussion of size effects for variable loading conditions in different geometries [27]. The parameter $M = b_0 \sigma_0 / J$ defines a non-dimensional loading and constraint parameter scaled to the specimen size (b_0 denotes the remaining ligament length). This non-dimensional parameter changes with corresponding J -values. As J increases, M becomes smaller. At smaller M -values and with stresses greater than yield strength, a material experiences more deformation. Therefore, M is also a measure of the extent of deformation in a specimen. As the remaining ligament decreases, the value of J also must decrease in order to maintain a constant M -value. For different geometries, if there are similar constraint levels and the specimens have equal M -values, the crack front normalized stress profile should be identical. With the constraint being the same in all of the FEA models, this should be the case for this Warp3D study. Any variation in the Warp3D normalized stress profile for the geometries in this study would indicate a mesh refinement issue.

If the mesh refinement in the models is small enough, the stress profile should be identical for all the samples. If the element size is too large relative to the overall

remaining ligament in the sample, or if the mesh is too coarse, the normalized crack front stress profile of the FEA models would not be identical because the accuracy of the output would decrease as the relative coarseness of the mesh increases.

7.5.2 Remaining Ligament to Element Size Effect

In order to determine the mesh effects, the three model sizes were run with $a/W=0.5$. During the deflection of the models, the crack was not allowed to propagate. This assured a constant a/W ratio for all J-values or loading conditions in the simulations. As stated earlier, since the constraint of the specimens was the same at a given M-value, the normalized stress profiles should have been the same. Three M-values ($M=25$, 10, and 5) were evaluated. As shown in Table 20, the study that was performed demonstrated that for a given M, as specimen size decreased, J decreased.

Table 20. Summary of Mesh Refinement Study

Specimen Size	Remaining Ligament, b_0 , in. (mm)	J at M=25 lbs/in. (kN/m)	J at M=10 lbs/in. (kN/m)	J at M=5 lbs/in. (kN/m)
0.1T	0.05 (1.3)	90 (15.7)	225 (39.2)	450 (78.4)
0.2T	0.1 (2.5)	180 (31.4)	450 (78.4)	900 (156.8)
0.394T	0.197 (5.0)	360 (62.8)	900 (156.8)	1800 (313.6)

The normalized stress profiles for the three conditions are shown in Figure 54 through Figure 56. As the size of the specimen decreased, the peak stresses dropped, indicating that there was a definite mesh effect occurring in the FEA models.

Figure 54. Normalized crack front stress profile for $M=25$ and $a/W=0.5$ for three TPB geometries.

For $M=25$ in Figure 54, the 0.394T TPB and the 0.2T TPB agreed well, but the 0.1T TPB model peak value was smaller. This indicated that the 0.1T TPB mesh was too coarse and that the element size was too large compared to the remaining ligament. This coarseness in the 0.1T TPB model resulted in under-prediction of the stresses at the crack tip. This effect resulted in no crack propagation as the void fraction in the cells never reached the critical value of 0.15. As M decreased to 10, as shown in Figure 55, there was more separation of the peaks and the curves for the 0.394T and 0.2T TPB, and the

Figure 55. Normalized crack front stress profile for $M=10$ and $a/W=0.5$ for three TPB geometries.

Figure 56. Normalized crack front stress profile for $M=5$ and $a/W=0.5$ for three TPB geometries.

specimens began to show greater deviation. When M decreased to 5, as shown in Figure 56, the element size for the 0.2T TPB and 0.1 T TPB models became too large for the remaining ligament. The Warp3D predictive capability failed for J-R with the 0.1T TPB and 0.2T TPB geometries.

To verify that the 0.394T TPB model was correct and that the model's behavior was similar to larger 1T CT samples, Dodds and Wasulik responded to a request to perform an independent test run on A516-70 steel for verification of the models in this study. Figure 57 demonstrates the similarity of the peak stresses of the 0.394T TPB model for this study—the results of the Dodds and Wasulik models were essentially the same [30]. The shift to the right in the 0.394T TPB curve was due to the normalization distance being affected by the J -values. The J -values for the two different sized samples were not the same at the same M -value, therefore, the relative distances shifted in the resultant curves. The results from Figure 57 also verified that the constraint was similar at an $M=25$ for the 1T TPB and the 0.394T TPB models.

7.5.3 Summary of Predictive Models

As shown in Figure 48, the Warp3D 0.394T TPB model predicted good agreement with the experimental J-R curve. This agreement verified that the mesh was refined enough for prediction of crack growth and toughness for 0.394T TPB samples

Figure 57. Normalized crack front stress profile for $M=25$ and $a/W=0.5$ for 0.394T TPB and 1T TPB models [30]. Source: B. Wasiluk and R.H. Dodds, *unpublished results* (March 2005).

with an element size of 0.004" (100 μm). The 0.2T TPB experimental and model data agreed only up to 4 mils (100 μm) of crack growth and a J-value of approximately 450 lbs/in. (78.4 kN/m) or to about an M equal to 10. Beyond this, there was no agreement with the J-R curve. This evidence showed that up to approximately $M=10$, the 0.2T TPB model had fair to good agreement; beyond this, there were mesh effects which contributed to the error in the output. This was further supported by the severe deviation of the 0.2T TPB theoretical FEA J-R curve and the experimental J-R curve as shown in Figure 49. For all conditions for the 0.1T TPB models, there were mesh effects that resulted in errors. This was seen in Figure 54 through Figure 56 where the crack front profile was flat, and did not match any of the other models. Clearly, the smallest model could not be used as a good predictive tool for J-R curve development. This was also supported by the deviation of the theoretical and experimental curves shown in Figure 50.

CHAPTER 8

SUMMARY AND CONCLUSIONS

The results of the experiments conducted in this research provide better understanding of the geometry size dependence of fracture toughness, demonstrate the value of the constraint parameter, M , as a good indicator for understanding accrued damage, and prove that the Warp3D code is effective in predicting cracks in samples as small as 0.394T TPB, but not for specimens smaller than this.

8.1 Summary

The testing of multiple-sized TPB samples in order to determine a limiting specimen size for the J-integral curves was successful; however, the tests did not meet the current requirements of ASTM. The smallest samples tested, 0.1T TPB and 0.2T TPB, were not able to produce $J_{0.008}$ values that were close to reported J_{IC} values of A516-70 steel. The 0.394T TPB specimens were able to reproduce $J_{0.008}$ values that were repeatable and comparable or equal to the J_{IC} values reported for this steel.

Typically, J-values increase with decreasing specimen size; however, at some point the specimens become so small that there is not enough volume to contain the actual plastic zone of the material, and the energy associated with its deformation is therefore smaller. This was true for both the 0.1T and 0.2T specimens. However, this

inability to duplicate J in the smaller samples does not preclude their use in understanding deformation in materials, as demonstrated by the use of the M -constraint parameter.

Application of the M -constraint parameter showed that even though the J -integral was not equal for the same amount of crack growth, the ability to associate relative crack growth with deformation was obtained in the 0.2T TPB samples. The use of M could reduce the required size of a sample that is needed for calculating values that correspond to larger samples. In essence, M could be used as a fracture limit in the way that toughness is used.

Currently, the toughness determination is dependent on whether a material has an M greater than 25. For two different sized samples of similar configuration at the same J -value, the associated M -values were not the same. In terms of relative amounts of deformation, the smaller sample would need to accrue a relatively larger amount of damage to have the same J -value. In essence, the two different sized samples with equal J -values represent two different damage conditions. Current standards dictate that toughness be measured at the same amount of crack growth of 0.008" (200 μm) regardless of the sample size. However, in two different sized samples that predict the same J -value, the M -constraint parameter has different values. This is because the relative amount of crack damage in these samples is different.

This work established that M is equivalent in the range of the same relative crack growth for the 0.2T TPB and the 0.394T TPB sized specimens. For a given M for a 0.2T TPB sample, there is an associated relative crack growth. Using the equivalent M approach, the amount of crack growth can be determined for a larger sample of the same

M-value, and the J-value can also be calculated at that M-value. The condition for use would be based on crack growth and M. For some amount of crack growth, the constraint parameter could not fall below some predetermined value in order to use the material in an application. Since M can be measured accurately using smaller samples than required for valid J measurement, in conditions where material availability is limited (such as with coring and in nuclear facilities), an M-curve could give indication as to the expected level of deformation.

There is a remaining question as to why the 0.1T TPB specimen did not yield the same M-curve. It is speculated that the side-grooving may have influenced the response by constraining the smaller samples less than the larger samples. Then notch sensitivity effect from the pre-cracking was also considered as a potential issue but was disregarded due to the close matching of the normalized load-deflection curves. If the notch had been a factor, the effect would have been seen in the curve response.

There was no crack growth for the very first 0.1T TPB specimen, however the load-displacement curve clearly indicated plastic deformation in the material. SEM examination of the fracture surface verified plastic distortion of the specimen with no evidence of crack growth. It is also important to recognize that ductile crack growth did occur in the 0.1T TPB sample at larger relative deflections or crack growth. The specimen was still large enough for ductile micro-void coalescence to occur. Even though there is evidence of competing mechanisms at play, ductile crack growth was still supported.

Notably, the J-value at crack initiation is still not known for any of the samples. Developing curves with data points that are obtained at lower load-deflection values would help to clarify what the curves look like at smaller crack growth. More detailed curves would also show how the M-curves would converge at lower relative amounts of crack growth. Prior to cracking, the J-value changes only as a function of plastic deformation and loading. M-curves should be developed for changing crack lengths for all geometries.

For FEA models, only the 0.394T TPB specimen accurately predicted the J-integral when modeled in Warp3D. The smaller specimens were not successfully modeled using the code. This is primarily attributed to the D/2 sized elements in the smaller samples being incapable of resolving the stresses and strains in front of the crack tip. This condition exists because the size of the element relative to the size of the modeled specimen is too large. As a result, the stress fields in front of the crack tip do not achieve high enough stresses to cause the model to simulate cracking or to reflect accurate predictions of the J-integral. Due to the inability of the FEA models to effectively resolve the stress fields in front of the crack, it is not possible to verify via computational methods if the deformation profiles in front of the crack tip are equivalent to the same M-value but different specimen sizes. The stress fields in front of the crack tips for the modeled 0.394T TPB and 0.2T TPB specimens do suggest that for equivalent higher M-values the stress profiles may be the same. For the experimental data, the J-R curves suggest that at M-values of 10, the modeled and experimental J-R curves are equivalent. However, due to the limited amount of testing material available, this was

not verifiable. It is definite that Warp3D cannot produce similar curves for the 0.2T TPB samples and that the characteristic length element size is too large for the specimen model to accurately predict crack growth.

8.2 Conclusions

This work produced a number of significant findings; here they are listed in summary form:

1. This work has verified that the 0.394T TPB samples for A516-70 steel are capable of measuring J-values comparable to larger sized 1T CT samples. However, for the 0.1T TPB and 0.2 T TPB specimens, tests on the samples were not able to predict comparable J-values for the same amount of crack growth.
2. This work demonstrates that the M-constraint parameter can be applied to explain crack growth for specimens that are much smaller than currently accepted by J_{IC} standards. It is hypothesized that this is due to the fact that the M-constraint parameter is a more geometry-independent value. Calculation of the same M-value represents the same relative damage and constraint level in specimens of different sizes. This effect was demonstrated in modeling by comparing the stress profiles in front of the crack for equal M-values of differing size models. The stress profiles for the 0.394T and 0.2T TPB specimens were very similar at M equal to 25. The 0.1T TPB showed no agreement to the larger samples for any M value. At lower values of M (M= 5 and 10), the 0.2T TPB stress profiles did not match the 0.394T TPB profiles. The variation of the crack front stress profiles is primarily attributed to the same FEA element size being used for both models and to the coarser resolution of the smaller sample.
3. The ability of the G-T model to predict crack growth was confirmed for the 0.394T TPB samples. The experimental and predicted curves overlaid well. However, for the smaller samples, the 0.1T TPB sample was not able to produce accurate crack growth. For the 0.2T TPB specimen model, it appeared that for crack growth between 4-8 mils (100-200 μm), Warp3D matched the J-integral curve. Beyond this amount of simulated crack growth, the experimental and predicted values deviated significantly. This was mostly due to the changing constraint state of the material. In the model, applying a pinned boundary

condition to the edges simulated the side-groove. In experimental work, the side-grooves did not constrain the specimen for the duration of the test, however, the models were constrained for the duration of the simulation. This condition was also true for the 0.1T TPB model.

4. The Warp3D element of 0.004" (100 μm) previously established for the A516-70 steel is too large for the 0.2T TPB and the 0.1TPB specimens. However, it is fine for a 0.394T TPB specimen. The percent limit of the element to remaining ligament for valid crack growth prediction is somewhere between 2-4%.
5. The use of the M-constraint parameter demonstrates that for small samples of 0.2T TPB and larger, the characteristic length from a relative damage and crack growth perspective can be measured effectively, and that the remaining ligament in these specimens is sufficiently large to resolve this. However, at 0.1T TPB size, the characteristic length is too large in comparison to the remaining ligament and does not yield equivalent M response as the larger samples. For the 0.1T TPB specimens, the characteristic length is still small enough compared to the remaining ligament to experience ductile crack growth. The smallest specimen used in this study still supports ductile crack growth.

8.3 Future Work

This work is just the start for refining a constraint and deformation parameter, M, for A516-70 ferritic steel and establishing methods for determining it for other ferritic steels. The M-constraint parameter needs more experimental data to thoroughly develop curves at higher M-values and lower relative crack growth so that the transition between ductile micro-void growth and crack initiation is better identified.

Further verification of M-curve application needs to be made by developing other materials curves as well as testing more samples of A516-70 steel and seeing how new data fit the existing developed curves.

Based on the findings in this work, there are several recommendations for further validation and clarification:

1. Develop and test specimens that are smaller than the 0.1T TPB specimen to identify where the characteristic length is too large to support ductile micro-void coalescence.
2. Test additional A516-70 samples of different geometries and sizes to verify and challenge the M-constraint curves established in this work.
3. Experimentally test multiple materials that are known to fail through ductile micro-void coalescence. Test multiple geometries that do not meet size requirements ($M < 25$) to determine the M-curves. This could help verify the use of M as a crack growth and toughness measure.
4. Using the computational cell model, determine the crack predictability threshold for element to remaining ligament percentage by developing models between the 0.2T TPB and 0.394T TPB specimen sizes.

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