5-2005

Fracture Toughness: Evaluation of Testing Procedure To Simplify JIc Calculations

Brandon Paul Pehrson
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Brandon Paul Pehrson entitled "Fracture Toughness: Evaluation of Testing Procedure To Simplify JIc Calculations." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

John D. Landes, Major Professor

We have read this thesis and recommend its acceptance:

J. A. M. Boulet, Arnold Lumsdaine

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Fracture Toughness: Evaluation of Testing Procedure To Simplify J_{Ic} Calculations

A Thesis
Presented for Master of Science
Degree
The University of Tennessee, Knoxville

Brandon Paul Pehrson
May 2005

DEDICATION

This thesis is dedicated to my parents, Paul Pehrson and Patsy Pehrson for their support and help, my brothers and sister, Heath Pehrson, Preston Pehrson and Stormi Gray and extended family for their encouragement and support.

ACKNOWLEDGEMENTS

I wish to thank all of those who helped me finish my Master of Science degree in Mechanical Engineering. I would like to thank Doctor Landes for his help in introducing Fracture Mechanics as a subject and for the help, encouragement and guidance that he has given me. I would like to thank Doctors Boulet and Lumsdaine for being on my graduate committee.

I would like to thank my parents for the support and encouragement that they provided to help me obtain a Master of Science degree.

ABSTRACT

The purpose of this study is to examine the current fracture toughness test procedure and to determine if there is an easier, less complicated method to get the J_{Ic} value from a test record for fracture toughness specimens. The current method for constructing J_{Ic} is complicated and involves a detailed computer program or spreadsheet. The objective in this study is to simplify the analysis for the determination of J_Q.

This study has shown that the load and displacement record for a fracture toughness specimen can be used to directly estimate a J_Q value, a provisional value for fracture toughness, J_{Ic}. The maximum load point is used along with an adjustment factor for this direct estimation of the J_Q value. This J_Q value is equivalent to that obtained from the construction procedure, when a unit-sized specimen is tested, that is, a specimen with a width of 50 millimeters (2 inches) and a thickness of 25 millimeters (1 inch). Other sizes require a size adjustment factor, which is simply a function of the specimen width relative to the unit width. The adjustment factor proposed is a square root relationship between the width of the test specimen and a unit width. This shows that the effort required for the proposed new method of constructing J_{Ic} is less than that required for the construction method, the new method is simple in concept and requires a minimum number of calculations, and the method appears to produce values of J_Q which are comparable to those obtained from the construction procedure and may have less inherent scatter.

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Nomenclature

$\mathbf{A_{tot}}$ = Total area under load displacement curve
a = Crack length
$\mathbf{a_o}$ = Initial crack length
$\mathbf{a_i}$ = Crack length index
$\mathbf{a_f}$ = Final crack length
B = Specimen thickness (gross)
$\mathbf{B_N}$ = Net specimen thickness
b = Specimen un-cracked ligament length, b= W-a
$\mathbf{b_o}$ = Initial un-cracked ligament crack length
$\mathbf{b_i}$ = Incrementing ligament length
$\mathbf{b_f}$ = Final ligament length
$\mathbf{C_{LL}}$ = Load-line compliance
$\mathbf{C_1}$ = Multiplication factor to J-R curve fitting equation
$\mathbf{C_2}$ = Exponent to J-R curve equation
$\mathbf{C_{construct}}$ = Constants for LMN construction
D(T) = Disk shaped specimen
E = Modulus of elasticity
J = Non-linear fracture parameter
$\mathbf{J_{Ic}}$ = Fracture toughness based on J
$\mathbf{J_Q}$ = Provisional J_{Ic} fracture toughness
$\mathbf{J_{total}}$ = Total J determined using area under load displacement curve
K = Crack tip stress intensity factor
$\mathbf{K_{Ic}}$ = Fracture toughness using K
k = Multiplication factor
L = Constant used in normalization
M = 2 for construction of J_Q
M = Constant used in normalization
$\mathbf{M_{construct}}$ = Constants for LMN construction
N = Constant used in normalization
$\mathbf{N_{construct}}$ = Constants for LMN construction
P = Load
$\mathbf{P_{no}}$ = Normalized load
$\mathbf{P_{no\ max}}$ = Maximum normalized load
$\mathbf{R_{sb}}$ = Strength ratio for bend specimen
$\mathbf{R_{sc}}$ = Strength ratio for compact specimen
$\mathbf{v_{el}}$ = Elastic displacement
$\mathbf{v_{pl}}$ = Plastic displacement
$\mathbf{v_{tot}}$ =Elastic and plastic displacement
W = Specimen width
$\mathbf{\Delta a}$ = Crack growth increment
η = Coefficient in J calculation, (η=2.15 for compact specimen), (η=2.0 for bend specimen)

σ_{Flow} = Flow stress
σ_{UTS} = Ultimate tensile stress
σ_{Yield} = Yield stress

CHAPTER 1: INTRODUCTION

Fracture mechanics deals with the behavior of structures and material with crack-like defects. Fracture toughness is defined as a generic term for measuring a material's resistance to the extension of a crack [1]. A higher toughness material resists crack growth at higher loading better than a less tough material. Many failures have occurred as a result of fracture, which can occur even thought the yield stress is not exceeded. Fracture was studied after a number of failures that involved crack-like defects in the structure. Some examples of fracture based failures were: a molasses tank explosion of 1919 in Boston, Liberty ships cracking during World War II, rocket motor case failures in the space program [4, 5, 6].

A molasses tank failed in 1919 in Boston, Massachusetts [4]. A tank holding two million gallons of molasses burst and a ten-meter high wall of molasses flooded the streets. The holding tanks were not designed with crack growth in mind. A crack grew on a cold day and the tank exploded. At the time the cause of the tank explosion was a mystery and the reason for failure was not understood.

The Liberty ship problem was a combination of new technologies [5]. New welded ship hulls were faster to build than riveted ships. The riveted ships did not have problems breaking in half because a crack would stop at the joint of the plates. The welded hulls allowed cracks to grow continuously along the ship hull. The Liberty ships would get into cold water where the fracture toughness of the steel was reduced and the ships experienced cracking problems with several of them splitting in two and sinking. The Liberty ship failures created a renewed interest in research studies into the causes of these failures. The United States Navy wanted to know how to build ships that would not fail by fracturing in cold water. The study by the Navy was an important step in understanding fracture related failures.

Hydrotesting a solid rocket motor casing for the NASA space program caused a highly documented failure [6]. NASA was hydro testing a 660 cm diameter rocket motor casing for solid fuel rockets. The rocket motor casing consisted of welded sections that formed a tube. During the hydrotest the welded casing ruptured at 56% of the planned pressure rating. The pieces were examined and crack growth was observed to be the cause. The cracks started from flawed weld joints and cracks continued to grow until the casing ruptured. The rocket motor failure led NASA to promote the organization of an ASTM committee activity that led to the development of the first standardized method for fracture toughness testing.

The standards developed for fracture mechanics allowed for constancy of fracture toughness results. The standards required uniform test specimens, testing procedure and analysis of the results. The American Society for Testing and Materials (ASTM) Committee E 24 on Fracture Mechanics developed the first standard for fracture testing standard; it is ASTM standard E 399; the standard method for K_{Ic} testing [1]. The fracture toughness test for K_{Ic} is strictly for linearly elastic materials. Many engineering materials fail under non-linear conditions and a need for a non-linear fracture toughness standard became apparent. ASTM published a standard for testing non-linear fracture behavior, one that could be used for large plastic behavior in the fracture specimens, in 1981. This was standard E 813; it was based on the J integral and resulted in a J_{Ic} fracture toughness value [2]. As the approaches to fracture toughness testing developed, numerous test methods resulted. The most current standard E 1820 [3] includes both linear and non-linear fracture behavior.

The fracture mechanics methodology is used to reduce or prevent failures by fracture. The fracture toughness tests determine the toughness of a material; these toughness values can be used to set design limits to avoid fracture. Knowing when fracture mechanics should be used is important in design and safety.

Tests are performed according to the ASTM standards, so that the values for fracture toughness of a material can be measured. The testing and analysis methods currently used are very involved and complicated. The analysis of the data requires large amounts of calculations where errors can occur. An inter-laboratory exercise to study the current fracture toughness standard test methods (called a Round-Robin study), reveled both the complexity of the current fracture toughness construction methods and the potential for inter laboratory scatter [8]. A simpler, more direct method for determining the fracture toughness value without doing the complex construction and large amounts of calculations would be useful. By reducing the number of calculations required, the possibility for making errors could be reduced. A simpler method could save both time and cost for determining the fracture toughness values.

CHAPTER 2: BACKGROUND

Fracture mechanics is the study of the effects of crack-like defects in structures and materials on the load bearing capacity. The use of fracture mechanics allows a determination of the conditions necessary to avoid failure. This is usually given in terms of a critical load for failure or a critical defect size.

The orientation of the loading relative to the crack-like defect determines the mode of loading for fracture. There are three modes of loading depending on the loading orientation relative to the crack plane. The loading perpendicular to the crack plane is called opening mode or Mode I. Mode II loading is in-plane shear or sliding. The crack is loaded along the plane of the crack and parallel to the crack plane surface. Mode III loading is out-of-plane shear or tearing. The crack is loaded with shear loads out of the plane of the crack. Figure 1 shows the three modes of loading (All tables and figures are in APPENDIX A). The most damaging orientation is that for mode I, and all standard test methods use only that mode of loading.

There are two main branches for analyzing fracture mechanics. The analysis of the two main branches depends on the type of deformation experienced by the material during the test. The linear elastic fracture mechanics (LEFM) that is based on the parameter K. The LEFM analysis is for the case of linear elastic deformation and is relatively simple and quick to perform. When the deformation of the test specimen has plasticity then a non-linear method is required. A non-linear fracture mechanics or elastic-plastic fracture mechanics (EPFM), which uses several non-linear parameters, namely J and crack-tip opening displacement. EPFM methods are more complex than the simple LEFM analysis. However, non-linear behavior is encountered more often in the failures of real materials and structures. The linear elastic method is discussed next.

2.1 LINEAR ELASTIC FRACTURE MECHANICS

LEFM deals with predominately linear-elastic deformation; small areas of non-linear deformation can be ignored if they are within the limits set in the test methods. The LEFM methods are relatively straightforward and simple. The fracture toughness parameter for LEFM is K, the crack tip stress intensity factor; this K parameter is labeled K_{Ic} at failure. K can be determined from values of load and crack length. The K_{Ic} values are a material property determined by the ASTM standard E 399 [1]. The K_{Ic} values are determined from a point on the K-R curve and are a material property. The K-R curve is a plot of the parameter K versus crack extension. It shows that as the crack begins to grow, the resistance to its growth, R, decreases until a steady state is reached. The K-R curve is a shortened name for the crack growth resistance curve. A typical ductile material K-R curve is shown in figure 2.

When the limits for using the linear method are violated, the non-linear fracture methods have to be used. A parameter labeled stress ratio, R_{sc} or R_{sb}, can be used to determine whether LEFM of EPFM should be used. The R_{sc} is used for compact specimens and the R_{sb} is used for bend specimens. The stress ratio is a value of nominal crack-tip stress to material yield strength. An example of stress ratio for the compact specimen is equation (1).

$$R_{sc} = \frac{2P_{\max}(2W + a)}{B(W - a)^2 \sigma_{ys}} \qquad (1)$$

When the R_{sc} is less than or equal to one, the LEFM method should be used. A value below one, means that the material behaves in a fully elastic manner. When the R_{sc} is above two, the material behaves in a fully plastic manner. When the material is fully plastic, the EPFM method should be used. When the stress ratio is in between one and two, the material is said to be in an elastic-plastic state. The methods for LEFM work better for R_{sc} is closer to one and EPFM work best with R_{sc} that is above two. The equations for R_{sc} and R_{sb} are in the ASTM standard E 399. Next the non-linear or elastic-plastic fracture mechanics methods are discussed.

2.2 ELASTIC-PLASTIC FRACTURE MECHANICS

When R_{sc} is greater than one the EPFM method is used. Non-linear fracture includes the deformation from elastic and plastic components in fracture analysis. The non-linear fracture mechanics methods are more complicated than LEFM methods; the incorporation of plasticity into the analysis complicates the analysis. One fracture toughness parameter used for non-linear fracture mechanics is the J integral. The determination of J includes load, load-line displacement and crack length.

The basic fracture toughness characterization by the J integral for ductile materials is the J-R curve, which is a plot of J versus ductile crack extension, Δa. Figure 3 shows a typical J-R curve. Often a single value of toughness is defined to simplify the analysis of fracture potential. To get a single point toughness, a point on the J-R curve is determined by a construction procedure. This point is labeled J_Q, a provisional value that becomes J_{Ic} when criteria t in the standard are me.

2.3 MULTIPLE SPECIMEN R CURVE CONSTRUCTION

The two main methods for development of R curves are the multiple specimen technique and the single specimen method. The multiple specimen technique involves testing five or more identical specimens with each specimen loaded to a different point on the load versus displacement curve. The specimens are first loaded to the desired point, then unloaded, and finally heated to mark the crack growth by oxidation. The specimens are then cooled in liquid nitrogen and broken open. The initial and final crack lengths are measured optically on the fracture surface. From this the J value is calculated at the final load point. These values, J and crack growth, Δa, are used to plot the J-R curve.

Because of cost for each test, it is desirable to use as few specimens as possible. For each test a specimen needs to be fabricated, pre-cracked and tested. The fabrication and pre-cracking of the specimens can take a considerable amount of time. The accuracy of the test also depends on the number of samples tested. The more samples tested the better the J_Q result.

2.4 SINGLE SPECIMEN R CURVE CONSTRUCTION

The single specimens method for construction of J-R curves requires that only one specimen be prepared and tested. The specimen must have crack monitoring equipment to determine crack growth. A crack can be monitored by optical measurements, compliance methods or an electrical potential system. The single specimen method requires measuring or calculating the crack growth continuously or at a discrete number of points for the specimen and then plotting the J versus Δa curve. The advantage of the single specimen test method is that only one specimen has to be fabricated and tested to determine the entire R curve.

Among the different single specimen methods for determining the J-R curve, only the compliance method is accepted by ASTM. The compliance method uses unloading and reloading to develop elastic slopes. These slopes are related to crack length using a compliance calibration equation. From the individual crack length measurements and values of J calculated at each point, the J-R curve can be determined. The elastic unloading compliance method is favored because it lends itself well to computerized data collection and analysis. However, the method is often difficult to use and requires good set up and experience. The fixtures have to be aligned properly in order to get good results. Noise from the testing equipment can cause some errors for measuring the compliance. Measuring the compliance requires that the gauges be very accurate. When bad alignment or noise interferes with the test, the crack length measurements may have a great deal of variability. The crack may appear to first grow larger and then smaller, an unrealistic possibility. Measuring the crack by compliance is difficult and many laboratories have trouble getting the compliance measuring equipment to work. The automated compliance method requires a good amount of experience. Once the J-R curve is determined by these compliance measurements, the analysis procedure in the standard is used to determine the J_Q value.

2.5 THE R CURVE SHAPE AND USE

A ductile material fails by coalescence of micro-voids; the development of the micro-voids causes an increase in slope of the R curve. A material that fails by cleavage results in an unstable fracture and an R curve does not develop. When the failure mode changes from predominantly ductile micro-void coalescence to cleavage, the R curve will suddenly terminate.

The R curve is used to determine the fracture toughness value of a material. A point is selected on the R curve as the fracture toughness value. When a single value of fracture toughness is determined for ductile fracture, the point is called J_{Ic}. The J_{Ic} value is a point determined by a construction procedure on the J-R curve and originally is called the J_Q value. J_Q is a trial or provisional value of J_{Ic}. The J_Q value has to meet specific criteria before the point is accepted as J_{Ic} value. The current method for determining J_Q requires a detailed construction procedure that sometimes allows for errors or inconsistencies in the analysis.

2.6 DETERMINATION OF J_Q POINT

The construction procedure for determining the J_Q point is explained in full detail in a later section. The J values determined from the data were plotted versus crack growth. A line is drawn at $\Delta a = 0$, the slope of this line is used to draw two other lines offset at 0.15 millimeters and 1.5 millimeters. The data inside the two offset lines is included in further analysis. The data also have to lie below the maximum J limit and lie within the crack growth limits. The data not excluded is by the lines and limits, is fitted with a power law. A third offset line at 0.2 millimeters is drawn, were the line intersects the curve fit of the data determines the J_Q value. The J_Q value is a provisional value of fracture toughness. The J_Q value becomes a J_{Ic} value when the validity requirements in the ASTM standard were satisfied. A typical construction plot with all the construction lines is shown in figure 4.

2.7 DIFFICULTY WITH CURRENT ANALYSIS

There are problems with the current analysis method. These problems include difficulty with both the multiple and single specimen methods for determining J. The J-R curve and the subsequent construction procedure used to determine J_Q from the J-R curve are a cause for variability in the J_Q value.

The multiple specimen tests require the use of five or more specimens. The specimens need to be fabricated, and pre-cracked before any testing can be started. Making five or more specimens could be expensive when testing a new material. Pre-cracking the specimens takes time and ties up equipment. The more specimens used to determine the J-R curve the better the results. After testing the specimens the crack locations need to be measured. Measuring the initial and final crack points takes time. The possibility for making and error while measuring on multiple specimens is increased.

The problems with the single specimen method are related to the compliance method. This method is often difficult to get to work. Problems from set up of the fixtures and gauges effect the compliance. Noise form the testing machine can create errors in the compliance. When the compliance method does not work a normalization method can be used. The normalization method is calculation intensive and requires a computer-spread sheet or programs. When testing large specimens there may not be a sufficient number of development data points in the area defined by the two exclusion lines. With a small amount of data in the analysis area, the fitting constants created from the power trend line do not accurately portray the shape of the R curve.

The difficulty with the current J_{Ic} test method and potential variability caused by the analysis gives a reason to try to find an easier and more reproducible method for determining a J_{Ic} value.

2.8 OBJECTIVE

The purpose of this study is to find a less complicated method for determining J_{Ic} fracture toughness values. Currently the determination of J_{Ic} is based on a construction process that is complicated and time consuming. Eliminating the need to do a large number of calculations saves time and reduces chances for making errors. The idea pursued her is find a characteristic point on the load displacement curve that gives a J_Q estimate close to the J_{Ic} value obtained by the rigorous construction procedure given in the standard test procedure. If such a point is identifiable, a J_Q value could be estimated with much less work. The value may not be the exact fracture toughness of the material. An exact value would require doing the present procedure. However, this estimation could provide a satisfactory estimation of the J_Q fracture toughness value.

CHAPTER 3: PROCEDURE

3.1 SPECIMEN PREPERATION

The most commonly used specimen for fracture toughness testing is the compact specimen. It is rectangular in shape, with thickness half of the width. The dimensions of the compact specimen are labeled width (W), total thickness (B), notched thickness (B_N), crack length (a), initial crack length (a_o), final crack length (a_f) and un-cracked ligament (b). A compact specimen is constructed according to the ASTM standard for fracture toughness testing. A typical compact specimen with dimensions labeled is shown in Figure 5. All but three of the specimens used in this work were of the compact geometry. The most commonly used specimen size is 50 millimeters or two inches in width. In this study the 50 millimeter specimen size will be taken as a unit sized specimen. The 25 millimeter specimen is becoming popular for new materials testing and irradiation tests. Since the cost of some new materials is high it is often better to test as small amount of material as possible. When irradiating specimens it is desirable to limit the specimen size because there is limited space in the capsules for irradiating specimens.

The data used in the analysis consisted of nineteen 50 millimeter specimens and eleven other specimens other than 50 millimeters. The 50 millimeter specimen size was chosen as the unit size in this work.

Test specimens must be fatigue pre-cracked before they can be tested. Pre-cracking creates a sharp crack tip. The pre-cracking procedure is given in each of the ASTM standards. The prepared specimens must be fully heat treated to the test conditions for fracture toughness before pre-cracking is performed. After the pre-cracking operation no intermediate treatments are allowed to the test specimen. The specimen can only be side grooved after pre-cracking. Side grooving produces nearly straight crack fronts.

3.2 TEST PROCEDURE

The test procedure involves loading a pre-cracked specimen to the fracture point or to a predetermined load or displacement point. During the test, the load and displacement for the specimen are measured. Additional measurements can be taken to determine crack length if such equipment is available. Test machines can measure compliance by unloading and reloading the specimen many times during a test; this method includes the crack growth on the data output for the test. The compliance is calculated from the reciprocal of the slope generalized by the unloading and reloading procedure. The compliance is then used to determine the crack length. Compliance is related to crack length using a calibration equation given in ASTM E 1820. Figure 6 shows a typical compliance un-load reload curve.

The specimen is broken open after the test to reveal the fracture surface in order to measure the initial and final crack lengths. The initial and final crack lengths are measured at nine different points through the thickness and an averaged value is used.

In this study test results were taken from the literature. These include tests conducted at Westinghouse Research and Development Center [9], GKSS Forschungszentrum, Geesthacht [8], and tests used for the ASTM round robin exercise where the origin of the material and data was not revealed [8]. The Westinghouse data include some large specimen tests. The specimens B1 and B2 are large specimen tests conducted at Westinghouse [9]. B3 is a unit-sized specimen of same material. The material for B1, B2 and B3 is an A508 steel, a reactor pressure vessel steel. The specimen dimensions for the Westinghouse R&D tests are in Table 1. Material properties for the Westinghouse R&D data Table 2. The GKSS tests specimen dimensions are in Table 1. GKSS is a European company that conducted some of the Round Robin tests. Material properties for the GKSS data are in Table 2. The material designations for the GKSS are A1 through A12. The round robin test specimen dimensions from the undisclosed laboratories are in Table 3. The material properties for these specimens are in Table 4. The unknown round robin specimens were designated C1-C16.

The total number of specimens in the study was thirty-one. Fifteen specimens were used to construct the J_Q point using the current ASTM standard analysis procedure. Nineteen other specimens from the Round Robin program used several different laboratories and graduate students to determine the J_Q values. All thirty-one specimens were used to estimate the J_Q values using the new method explained in chapter 5. The standard analysis procedure for determining the J_Q point is described in chapter 4.

CHAPTER 4: DATA ANALYSIS

The data were analyzed according to the ASTM standard E 1820 using the equations for compact specimens. The analysis also follows the method given by Kang Lee for normalization using the LMN constants [7]. The normalization method is used to determine the crack growth without the use of crack monitoring equipment. The procedure for determining the fitting constants, LMN, is explained in greater detail in a paper by Landes et. al [10].

The basic data collected from the tests were in the format of load versus displacement. An example of a load versus displacement curve is given in figure 7a. The specimen dimensions along with the measured initial and final crack length were used in the analysis. The modulus of elasticity can be computed from the load and displacement record, but the flow stress must be known from tensile tests. The flow stress was the average of the yield and ultimate tensile stresses at the test temperature. The flow stress is used in the construction procedure to determine the J_Q value. The data were analyzed to determine crack growth using the normalization method.

The compliance is used to separate the plastic and elastic components of displacement from the test record. The equation for computing compliance is in the ASTM standard E1820. The original crack length is used for the compliance calculations. The elastic component of the displacement is determined from the load by using Eq. (2). The total displacement is a combination of elastic and plastic displacement as shown in Eq. (3). The plastic displacement is determined by subtracting the elastic displacement from the total displacement, Eq. (3).

$$v_{el} = P_{(i)} * C_{LL(i)} \qquad (2)$$

$$v = v_{el} + v_{pl} \qquad (3)$$

After the two components of displacement were determined, the load could be normalized to eliminate size and crack length dependence. A normalized load, P_N versus a normalized plastic displacement, v_{pl}/W is plotted. This normalized load versus normalized plastic displacement curve is a plot of the specimen plastic deformation character; it can be fitted. With a function that uses three unknown fitting constants L, M and N to fit the deformation shape. The plastic component of displacement is needed to determine the M and N fitting constants. The constants M and N have to be solved simultaneously. The constant L is determined by using the maximum normalized load. Equations (4) and (5) were arranged into a matrix form used to determine the M and N constants, explained later in greater detail later.

$$P_{no(i)} = \frac{P_{(i)}}{WB\left(\frac{b_o}{W}\right)^{\eta_{pl}}} \qquad (4)$$

$$P_{no(i)} = \frac{L + M * \left(\frac{v_{pl}}{W}\right)}{N + \left(\frac{v_{pl}}{W}\right)} * \left(\frac{v_{pl}}{W}\right) \qquad (5)$$

The maximum load was selected from the data and was used as the L coefficient for the normalized load fit for crack growth. The value of L can be multiplied by 1 to 1.12 depending on the value of N. When the fitting constant N was less than 0.0006, the value of L can be multiplied by k. The k values range from 1.0 to 1.12. The constant k is explained further in the dissertation of Kang Lee [7]. L, M, N are all the fitting constants used in the calculation of crack growth. Equation (6) shows the calculation for the L constant.

$$L = \frac{P_{no\max}}{WB\left(\frac{b_o}{W}\right)^{\eta_{pl}}} * k \qquad (6)$$

The values of M and N were calculated using Eq. (4) and (5). The loads for each of the equations must be equal so the N and M constants can be calculated. The known normalized load ($P_{no(i)}$) was used for Eq. (4) and the constants are solved from Eq. (5).

A simultaneous solver was used to solve at each value on the load displacement data points. Equation (7) was the equation set up for determining the N and M constants. Equations (8), (9) and (10) were the values substituted into Eq. (7) to solve for the M and N values at every load and displacement point.

$$\begin{bmatrix} C_{construct(i)} \\ C_{construct(f)} \end{bmatrix} = \begin{bmatrix} M_{construct(i)} & N_{construct(i)} \\ M_{construct(f)} & N_{construct(f)} \end{bmatrix} \begin{Bmatrix} M_{(i)} \\ N_{(i)} \end{Bmatrix} \qquad (7)$$

$$C_{construct} = \frac{v_{pl(i)}}{W}\left(P_{no(i)} - L\right) \qquad (8)$$

$$M_{construct} = \left(\frac{v_{pl(i)}}{W}\right)^2 \qquad (9)$$

$$N_{construct} = -P_{no(i)} \qquad (10)$$

The upper row of the matrix contained the current line being analyzed while the lower line contained the last point of the measured data. The last line of data always contained the final crack length and final load in the data. The equations had to be solved simultaneously. A computer program was written to solve the values of M and N at every data point. The appropriate range of M and N values were selected from the data and averaged. The maximum data values for the M and N constants were determined by drawing a line from the final crack displacement point on the normalized load (P_N) versus plastic displacement divided by width (v_{pl}/W) diagram tangent to the curve, see Figure 7b. Where the line was tangent to the P_N versus v_{pl}/W curve located the last point usable in the calculated N and M constants. The minimum point used was the first point on the P_N versus v_{pl}/W curve that was in the non-linear portion. The L, M and N values were used to calculate the normalized load including crack growth. The normalized load using the LMN constants to calculate the load was Eq. (5).

The normalized load with crack growth and no crack growth were plotted versus the plastic displacement divided by the width. Solving for the crack growth at each load displacement data point Eq. (4) and (5) were used along with Eq. (11) resulting in Eq. (12). Equations (4) and (5) loads were set equal and crack length was determined. The LMN constants for determining the load and displacement include crack growth so the crack growth was calculated at every point. The un-cracked ligament for the initial crack length is b_o. As the crack length increases the un-cracked ligament decreases, Eq. (11) determines the un-cracked ligament with increasing crack length (b_i).

$$b_i = (W - a_i) \quad (11)$$

$$a = -\exp\left[\frac{\ln\left(P_{(i)}\left(\frac{N + \frac{v_{pl}}{W}}{\frac{v_{pl}}{W} * W * B\left(L + M * \frac{v_{pl}}{W}\right)}\right)\right)}{\eta_{pl}}\right] * W + W \qquad (12)$$

When the crack length is known at every point the values for K and J_{total} are calculated using the equations in the ASTM standard. J versus the crack growth is plotted in order to determine the provisional fracture toughness value, J_Q.

The J_Q is determined by a construction procedure that is described next. A construction line was drawn on the plot using Eq. (13) as the slope.

$$J = M\sigma_Y \Delta a \qquad (13)$$

Where M is usually taken as 2.0. Two exclusion lines are drawn offset at 0.15 and 1.5 mm the crack length, using the same slope as the construction line from Eq. (13). Only the data between these two lines are used for the analysis, all data outside of the exclusion lines are not used for the calculation of J_Q. The data in-between the exclusion lines are checked if in the maximum J integral and maximum crack extension limits. The maximum crack extension capacity for a specimen, Δa_{max} is given in Eq. (14). The maximum J integral capacity for a specimen, J_{max} is the smaller of Eq. (15) or Eq. (16). The limits for Δa_{max} and J_{max} do not show up on the graph because of the reduced scale. All data that meets these requirements can be used to determine the J_Q point. Equations (14), (15) and (16) given the limits as specified in the ASTM standard E 1820.

$$\Delta a_{\max} = 0.25 b_o \qquad (14)$$

$$J_{\max} = \frac{b_o \sigma_Y}{20} \qquad (15)$$

$$J_{\max} = \frac{B \sigma_Y}{20} \qquad (16)$$

The data falling between the exclusion lines are fitted with a power law, given by Eq. (17).

$$J = C_1 (\Delta a)^{C_2} \qquad (17)$$

Where C_1 and C_2 are fitting constants. Using the power law the shape of the R curve can be plotted. Another construction line was drawn offset at 0.2 mm. The J_Q value was determined from the intersection of the fitted line Eq. (14) and the 0.2mm offset line. Figure 4 shows a typical J-R construction for calculating the J_Q point. The J_Q value becomes a J_{Ic} value when the qualification requirements ASTM standard E 1820 are met.

The specimens labeled A and B were analyzed using the ASTM standard E 1820 method and the J_Q values were determined. The J_Q values for the specimens labeled C were already determined and documented in the round robin study. An example construction curve to find the J_Q point is in figure 8. The closest data point to the J_Q location is given as a solid point for identification and to use later. The points that were not between the two exclusion points were removed. The equation in the middle of the graph shows the constants C_1 and C_2 determined from the power trend line curve fit. The power trend line is the solid line on the plot. The maximum crack extension capacity and maximum J integral capacity are out of frame on the plot.

CHAPTER 5: SIMPLIFICATION STUDIES

The major idea for simplifying the J_Q evaluation process began with identification of the location of the load versus displacement value that is equivalent to the J_Q point determined by the construction procedure of E 1820. The load versus displacement curves for specimens A1 through B3 are plotted and the points that are equivalent to the J_Q values for the specimens were plotted on the curves. This point is located using spreadsheets to determine the point on the load versus displacement curve equivalent to the J_Q value. This analysis is made for a range of specimen sizes from a width of 25 millimeters to 508 millimeters. Two specimens are 25 millimeters in width, six are 50 millimeters in width, three are 100 millimeters in width, two are 200 millimeters and two are 508 millimeters in width. Each group of sizes is plotted separately. The 50 millimeter specimens plot of the J_Q on the load displacement curve is figure 9. The 25 millimeter specimens plot of the J_Q on the load displacement curve is figure 10. The 100 millimeter specimens plot of the J_Q on the load displacement curve is figure 11. The two 200 millimeter specimens did not get a valid value for J_Q, so the J_Q from the 50 millimeter specimens is used as the value for the plots. The 50 millimeter specimens J_Q value is used since the fracture toughness value because the same material has approximately the same J_Q value for different specimen sizes. Figure 12 shows the 200 millimeter specimen's load versus displacement curve with the J_Q point on the curve. The two 508 millimeter specimens also did not give a valid result for J_Q, so the J_Q value from the B3 specimen is used for the J_Q point. Figure 13 shows the 508 millimeter specimens load versus displacement curve with the J_Q point on the curve.

The location of the J_Q point on the load displacement curve for the 50 millimeter specimens shown in figure 9 is approximately at the maximum load point for all of the specimens. This is so for all six 50 millimeter specimen examples used in the analysis.

The location of the J_Q points on the load displacement curve for the 25 millimeter specimens is shown in figure 10. The J_Q points are past the maximum load point for both specimens. The location of the J_Q point on the load displacement curve for the 100 millimeter specimens shown in figure 11 is before the maximum load point for all three specimens. The location of the J_Q point on the load displacement curve for the 200 millimeter specimens shown in figure 12 is well before the maximum load point for both specimens. The location of the J_Q point on the load displacement curve for the 508 millimeter specimens shown in figure 13 is at the earliest point of all specimens.

Some observations about these plots can be made. The J_Q value fell at approximately the maximum point on the load displacement curve for the 50 millimeter specimens (2 inch), therefore, this size is taken as the unit size. The maximum point is a convenient point because it is easy to identify on the unit sized specimen. From this it can be concluded that the maximum load provides a good estimation of J_Q for the 50 millimeter specimens analyzed here. The J_Q for the specimens smaller than the unit size are farther along the load displacement curve, past the maximum load point. For specimens larger than the unit size J_Q falls before the maximum load point. The smaller specimens have a larger plastic component of plastic displacement than the larger specimens. The larger component of plastic deformation causes the J_Q point to fall farther out on the load versus displacement curve. The larger specimens have a larger elastic component of displacement than the smaller specimens. The hence the J_Q point fall earlier on the load displacement curve. This is reasonable because the larger the specimen, the larger the component of elastic displacement. As stated previously, specimens other than the unit size have a JQ value that is not exactly at the maximum load point; therefore, if J_Q is to be based on the maximum load point an adjustment must be considered. The procedure below describes how the calculation for J_Q on the unit size and the determination for other sized specimens is performed.

The simplified procedure uses the maximum load point to determine the J_Q value from the load displacement record. The calculation of the J_{total} using the total area under the load displacement curve is done using Eq. (18).

$$J_{total} = \frac{\eta\ A_{tot}}{b_o B} \qquad (18)$$

The constant η is 2.15 for compact specimens and 2.0 for three point bend specimens, from the ASTM standard E 1820. The total area (A_{tot}) under the load displacement curve is calculated so that J_{total} can be calculated. The total area under the load displacement curve is calculated using a trapezoidal rule for the data. The total area included all the area under the curve up to the maximum load point. Figure 14 shows the area used in the A_{tot} calculation. The crack length used in Eq. (18) to get b_o is the original crack length, a_o.

The J_{total} is used as the J_Q value for the three point bend specimens and unit sized compact specimens. For specimens other than the unit size an adjustment factor is used. To determine the adjustment factor many different ideas were tried. The first idea was a linear fit with the ratio of the unit width to that of the actual specimen width. This adjustment was not very accurate, causing the J_Q estimation to be shifted too much. A better fitting factor for the adjustment factor would shift the J_Q point less and would have to be non-linear. Since the behavior required a smaller shift a square root of the ratio of specimen widths, was chosen as the adjustment factor. The J_{total} was then used to calculate the J_Q for the specimen using the adjustment factor. Equation (19) is the adjustment factor used to get the J_Q values from the other sized specimens.

$$J_Q = \sqrt{\frac{50}{W}} * J_{total} \qquad (19)$$

The values for all 15 specimens were calculated and compared to the calculated J_Q values using the construction method. The new values are in Table 5 as $J_{Q\ new}$ and the current construction method values as J_Q. The J_{total} values without the adjustment factor and with the adjustment factor were plotted for each size specimen. Figure 15 is the estimated J_{total} value with the corresponding corrected J_Q value. The adjustment factor adds to the specimens smaller than the unit-sized specimen and subtracts from the larger sized specimens. The non-linearity is evident in the plot of J_{total} values.

For specimens with flat load displacement curves the noise in a test machine can cause oscillations in the load and an exact maximum load is difficult to determine. For these cases a point 1.0% to 0.5% before the maximum load is used as the loading point to determine the J_Q value. This approach eliminates the noise from the test machine, but give a slightly lower value of fracture toughness. This lower point should only be used on specimens with noise problems. Specimens A11 and A12 were specimens were this rule was applied. The noise was causing the load to oscillate up and down and many maximum points were observed on the load versus displacement curve.

To verify that the maximum load point method was approximating the J_Q value correctly, the J_Q values were tested using data with known J_Q values. The Round Robin data set with the known J_Q values contained several different strengths of steel and a multiple specimen test for aluminum. These data was analyzed by a diverse group including several laboratories with experience in this type of analysis and some graduate students who were relatively inexperienced. For each test record the J_Q values were estimated from the maximum load point method, Eq. (18), and were compared to the other laboratories' J_Q analyses. The values calculated from the different laboratories, graduate students and the new method are in table 6. Figure 16a through 16l shows the J_Q values determined by the different labs, students, and maximum load method. The J_Q data is the estimated J_Q value using the new maximum load method. The data labeled 0.1% P in the legend of Figures 16 is the new maximum load method for estimating J_Q with noise adjustment, that is using 99% of the maximum load for the estimation of J_Q. The Data J_{Ic} is the results from the experienced laboratories and graduate students that participated in the round robin exercise. The average in the bar graph is the average values of the Data J_{Ic} or average values of the laboratories and students analysis. The average value excludes the estimation form the new maximum load method. The material in Figures 16a and 16l is aluminum; the material in the other figures is steel.

Comparing Figures 16a through 16l shows that there is some scatter in the determined value for fracture toughness. Since these values are somewhat empirical, no one value can be taken as the exact value. Fracture toughness values that are within the range of previous toughness values are considered acceptable.

The average value cannot always be taken as the acceptable fracture toughness value. The averaged values of fracture toughness may not be the correct average if any one value has a large error or a value that is greatly different from rest of the values. Figures 16e, 16f, 16l are good examples of when any one value has a large error and is not within the range of the other values. By comparing the computed values from other laboratories the determined values of J_Q can be checked to see if any gross errors were made. The values from the new method were plotted and error bands were drawn to show the J_Q values determined from other laboratories. Figure 17 shows the plot of the J_Q from the new method for the C specimens, the error bars are the maximum and minimum J_Q determined by the Round Robin laboratory study. In Figure 17 specimens C1, C10 and C11 are outside of the error bands. These values are the only three that were out of the maximum to minimum region. The other specimens have the J_Q value inside the maximum to minimum region. Specimens C2, C10 and C11 are the three bend bar specimens.

CHAPTER 6: SUMMARY AND CONCLUSIONS

The J_Q point can be estimated directly from the load versus displacement curve by using a method proposed in this work. This estimation is based on a J value determined at the first occurrence of the maximum load point in a load versus displacement curve. The specimens with noise can use 99% or 99.5% of the load value to estimates the J_Q value. For unit-sized specimens (W=50 mm) this maximum load point gives a good J_Q estimation. The bend specimens also use the maximum load method for an estimation of J_Q. For other sizes the estimation of the J_Q requires an adjustment factor. This adjustment factor is used to shift the estimated J_Q from the J at maximum load for non-unit sized specimens. The three point bend specimens follow the same procedure as the compact specimens, except they do not use the adjustment factor; the J_{total} value is the J_Q value.

The new estimation method is not size dependent. The data analyzed appeared to be valid for specimens ranging from 25 millimeters to 508 millimeters. Further study to explore the range of the new method would require testing of many more different sized specimens.

The calculation using the new J_Q estimation method is much easier than the existing method of ASTM standard E 1820. Some of the variability inherent in using the standard method can be avoided. The new J_Q estimation method works well for specimens that deform plastically and are ductile. The new estimation method is a good technique for getting J_Q values when the current construction procedure fails. Using the new method, one can estimate a value from the tested specimen even when the construction procedure is not able to determine a fracture toughness value.

Further study would be desirable to see if this estimation method is more generally applicable. One idea for further study is to try this method for other materials. The study used only steel and aluminum specimens. Different materials behave differently and so this method may not work as well. Evaluation of the simplified method on polymers and alloys would be useful in determining the validity of the new method over a range of materials.

Also, different specimen geometries should to be evaluated. The compact specimen was the main specimen geometry and only three bend specimens were tested. Further evaluation of different specimen geometries and other specimen sizes would also determine whether this method is size and geometry insensitive. The study of the effect of material and geometry variables is a recommended topic for future work.

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APPENDICES

APPENDIX A

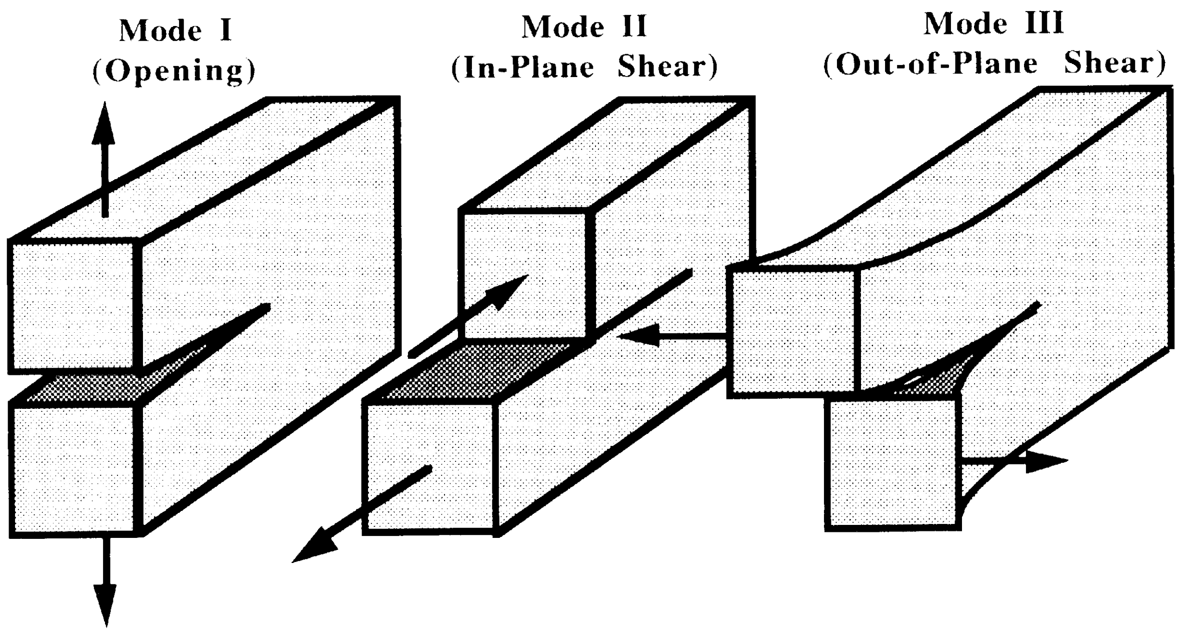

Figure 1 - Modes of loading on crack surface [5]

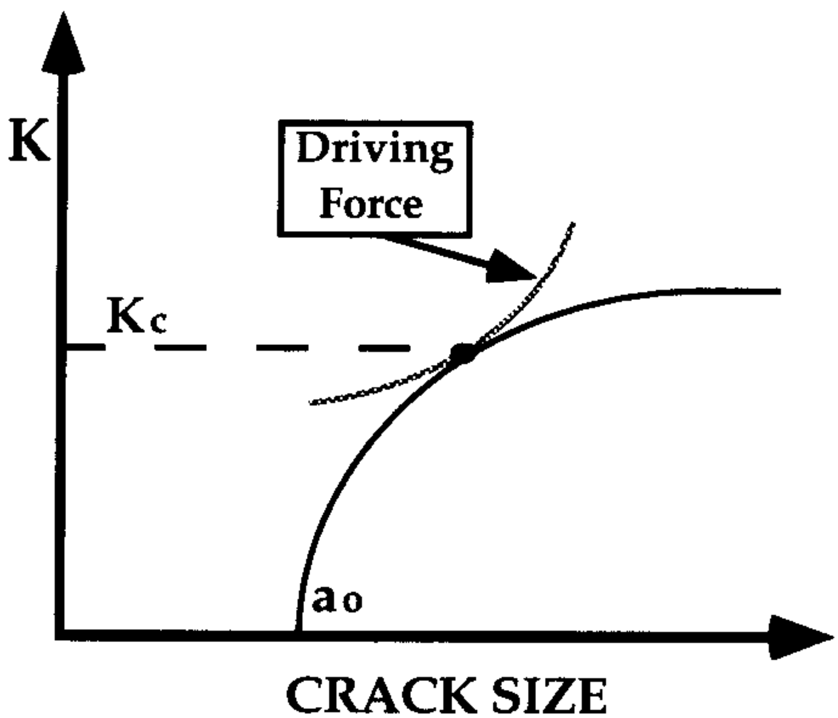

Figure 2 - Typical K-R curve [5]

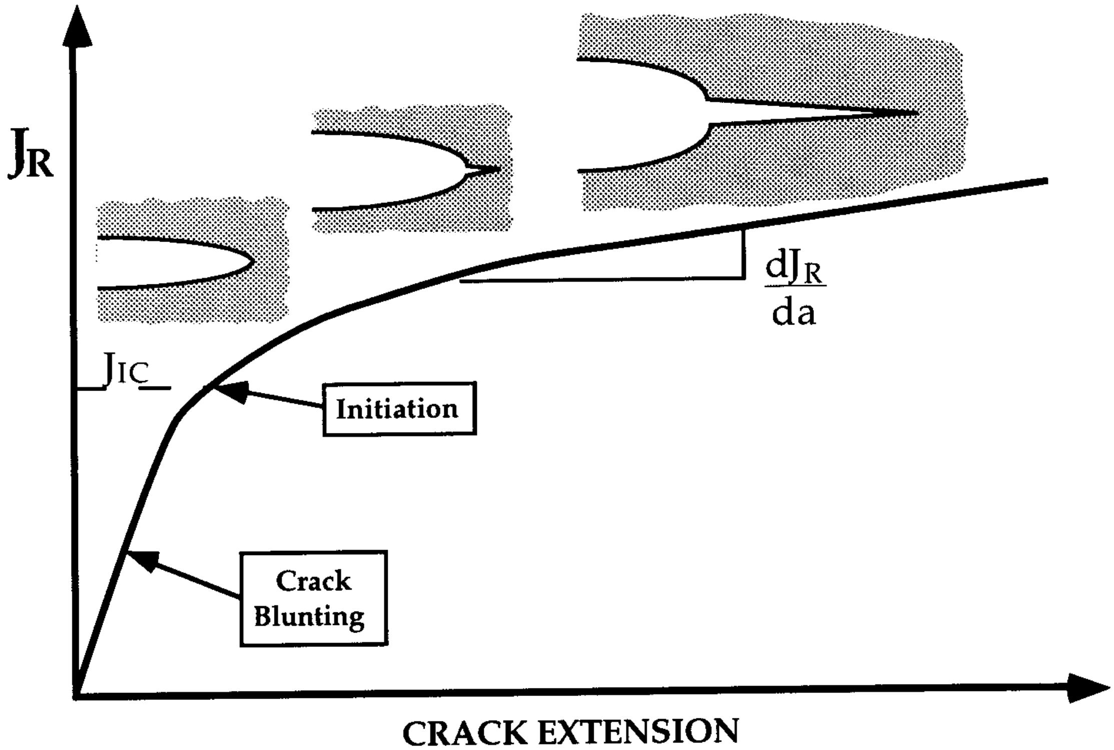

Figure 3 - Typical J-R curve [5]

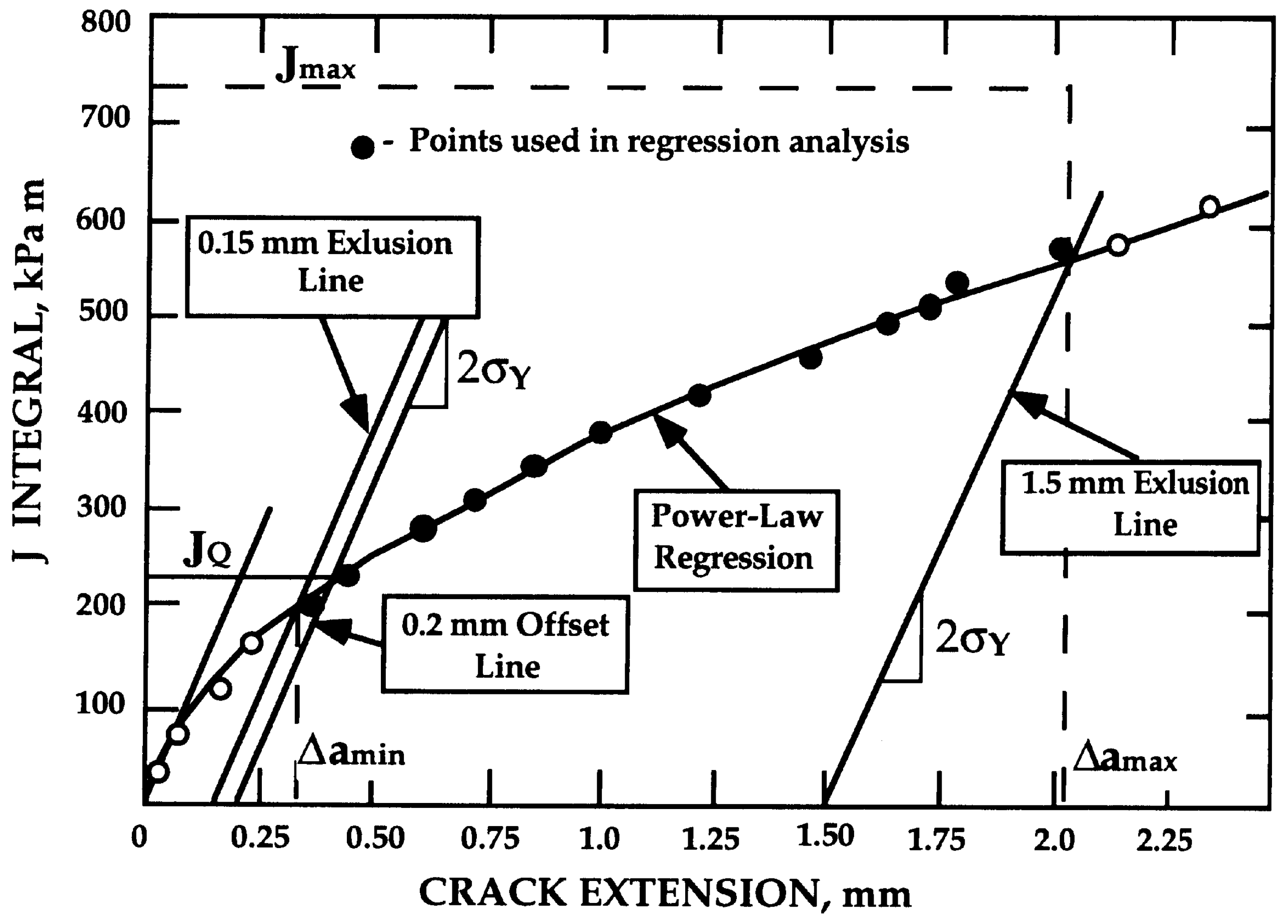

Figure 4 - Typical J-R curve construction and shape and analysis [5]

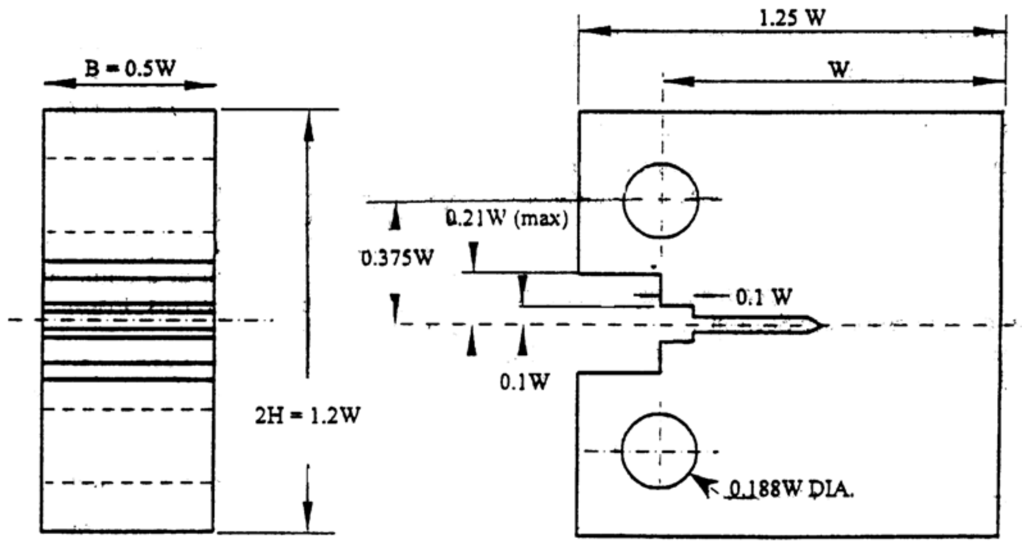

Figure 5 - Compact specimen geometry and dimension [3]

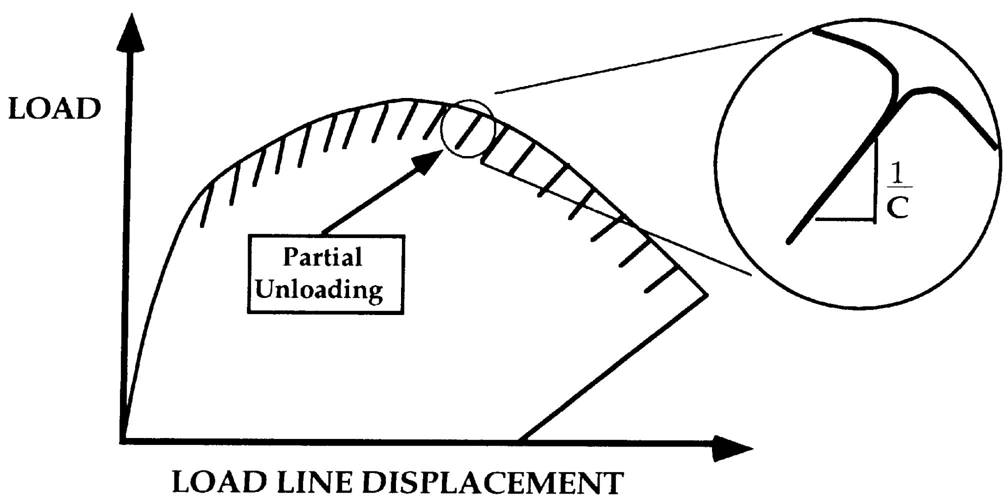

Figure 6 - The Elastic Unloading-Reloading Compliance Method for monitoring Crack growth during fracture testing [7]

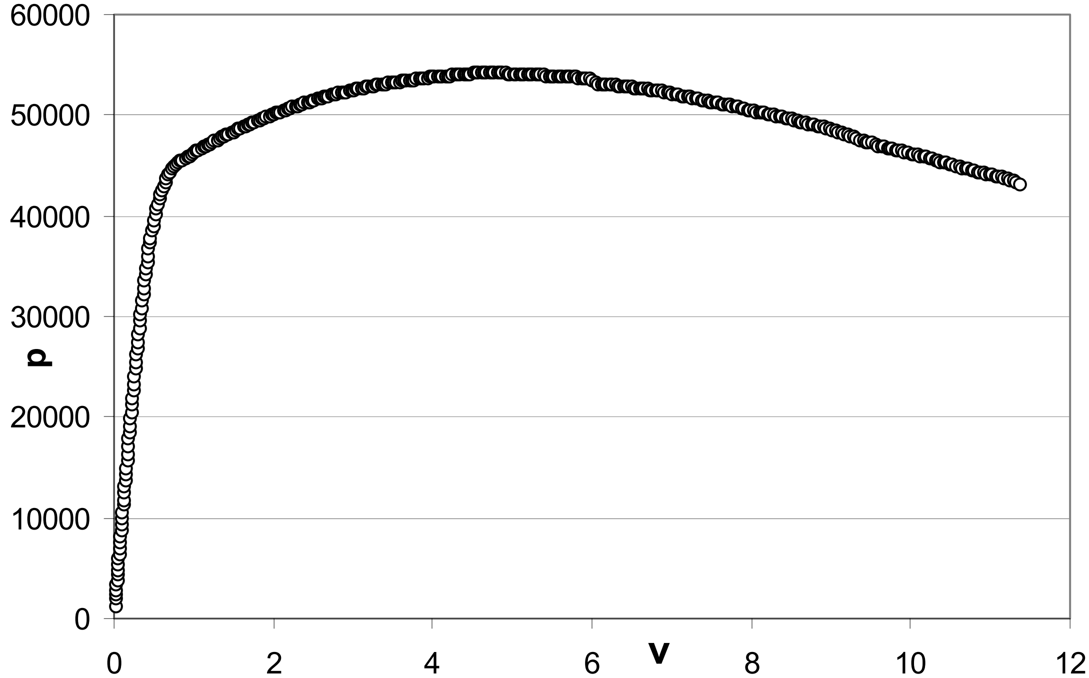

Figure 7a - Typical load displacement curve

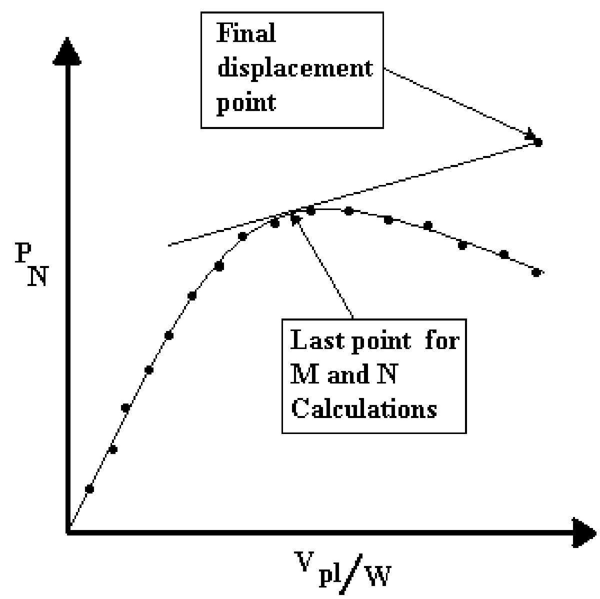

Figure 7b – Location of maximum data points for the calculation of normalization constants M and N

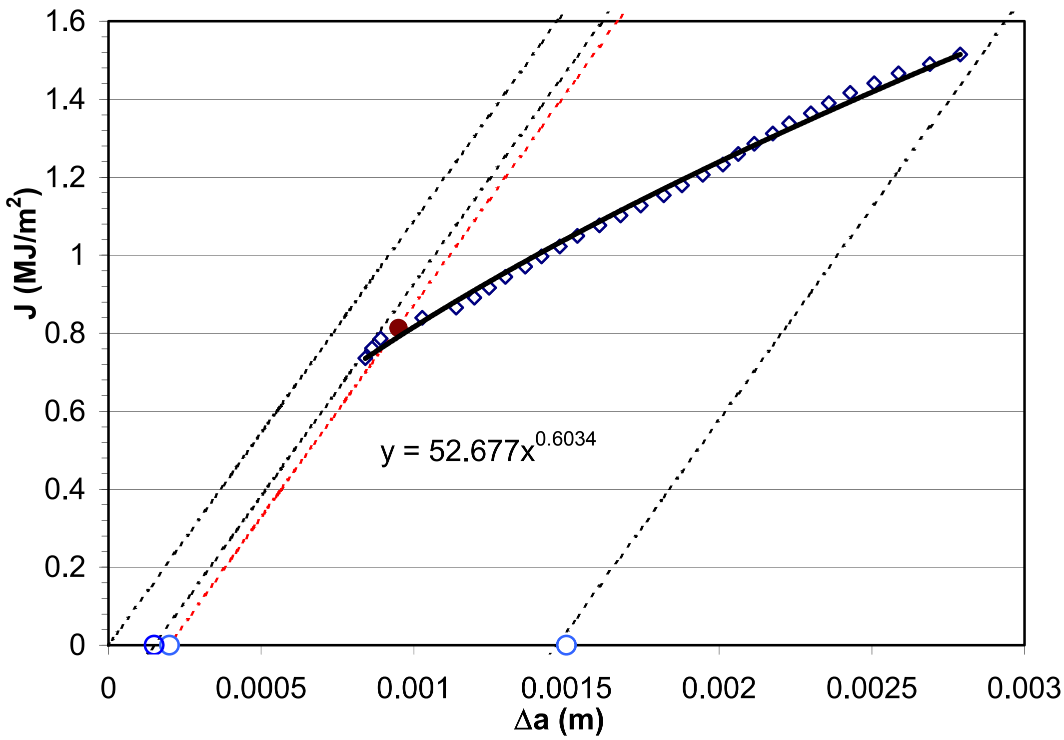

Figure 8 – Construction example of compact specimen.

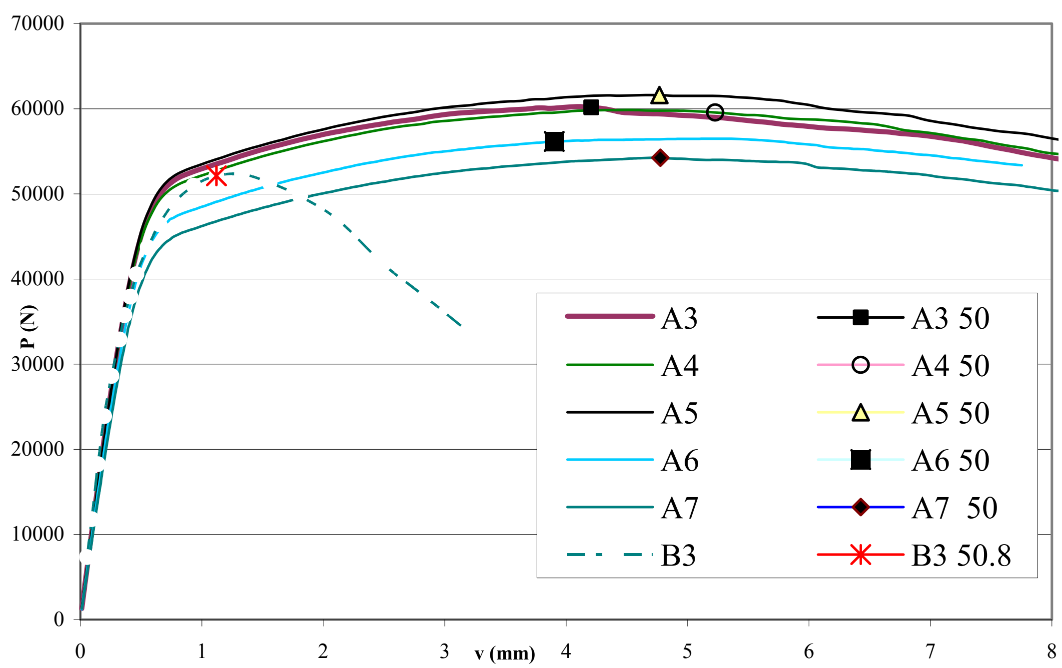

Figure 9 - 50 mm specimens J_{Ic} points

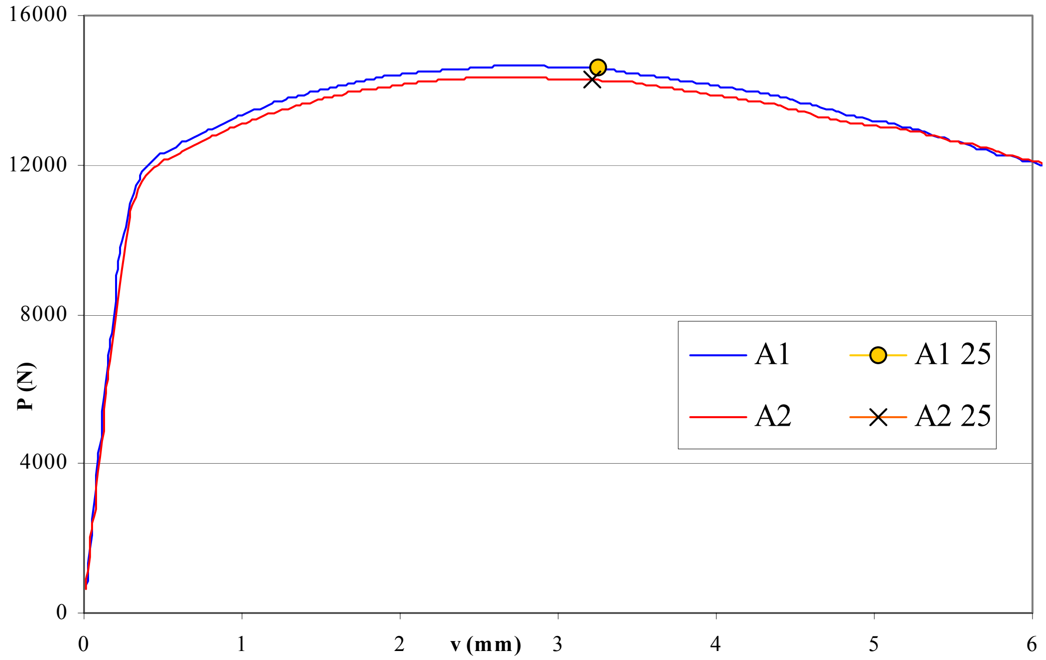

Figure 10 - 25 mm specimens J_{Ic} points

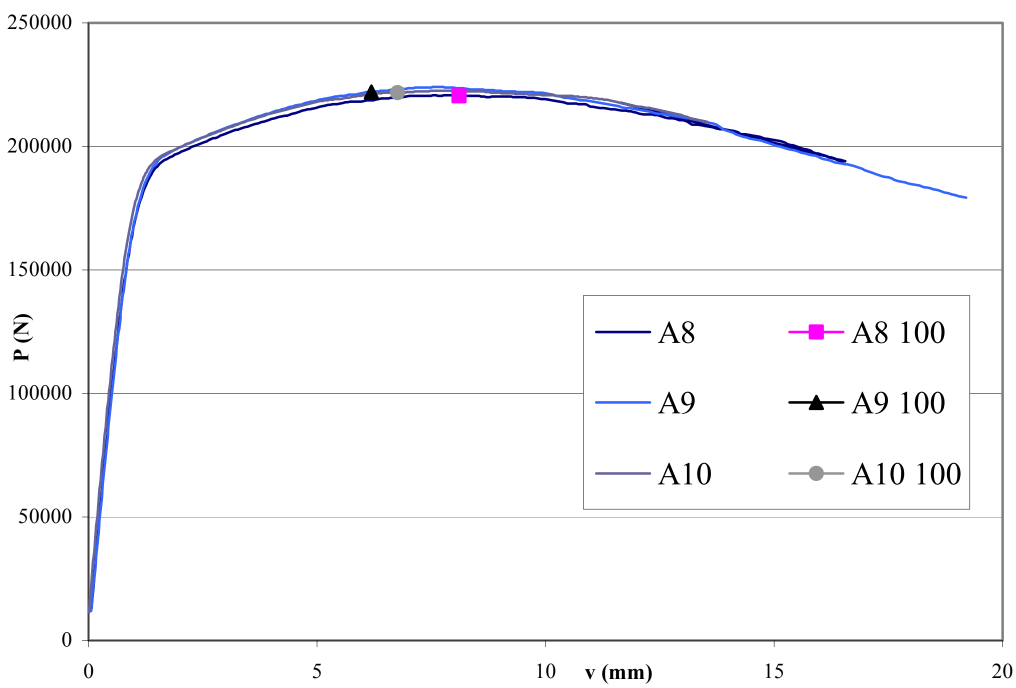

Figure 11 - 100 mm specimens J_{Ic} points

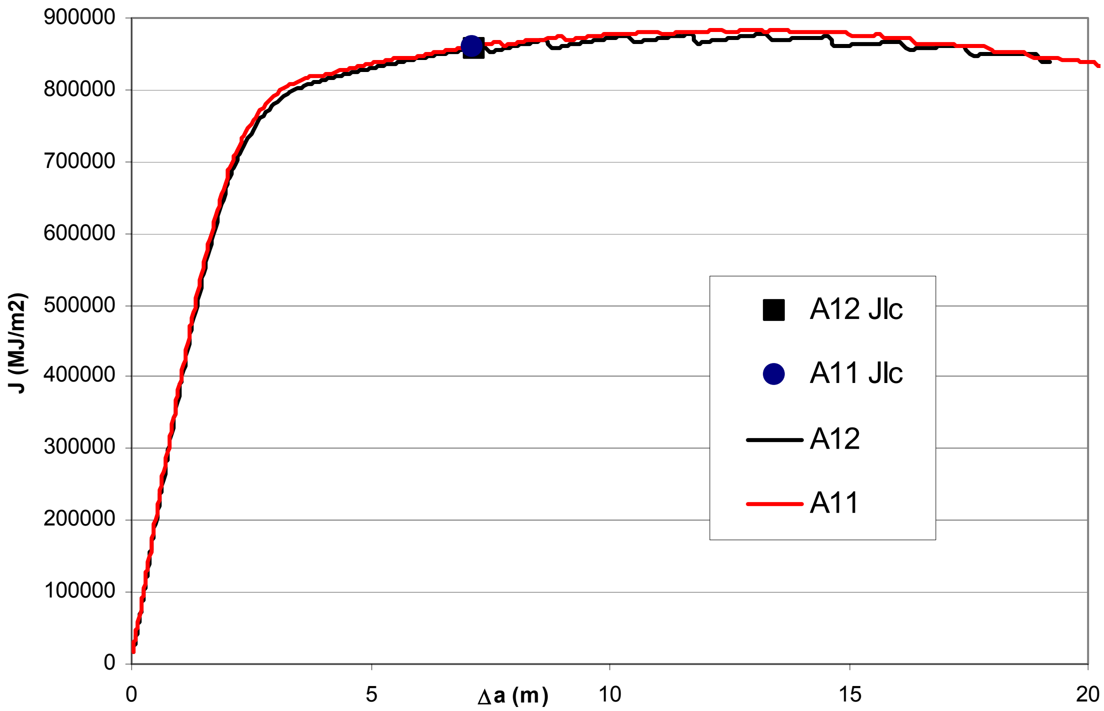

Figure 12 – 200 mm specimens J_{Ic} points

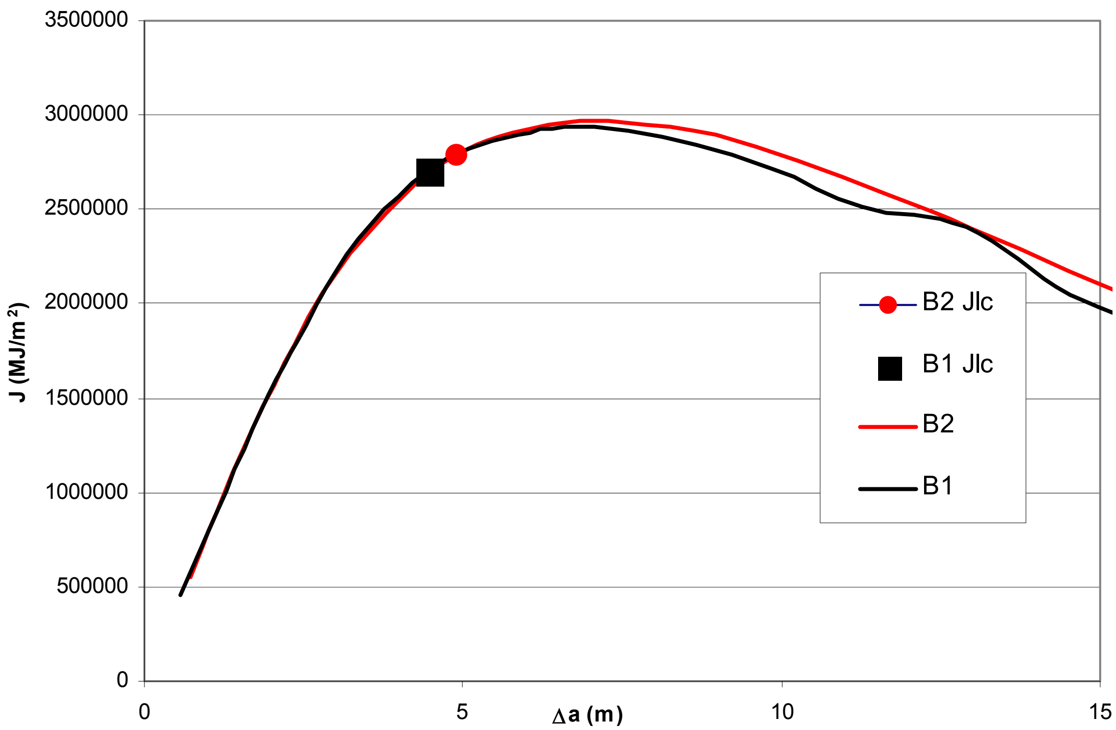

Figure 13 – 508 mm specimens J_{Ic} points

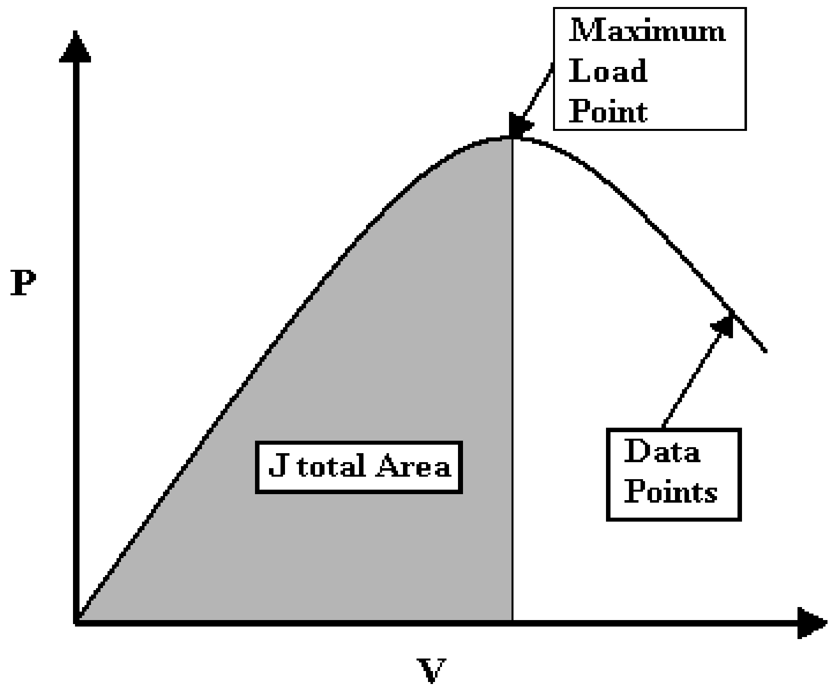

Figure 14 – Area used in new method for determination of J_Q

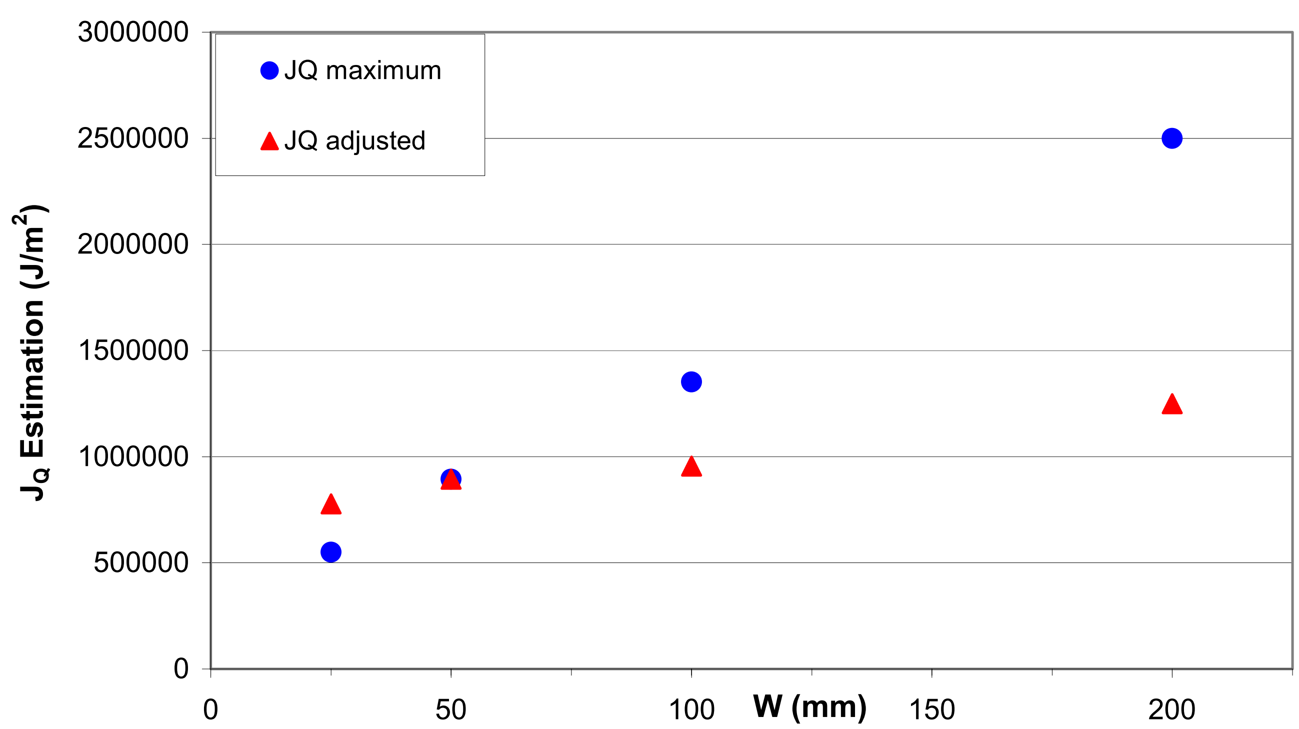

Figure 15 - The J_Q estimated value with the corresponding corrected J_Q value for different sizes of specimens

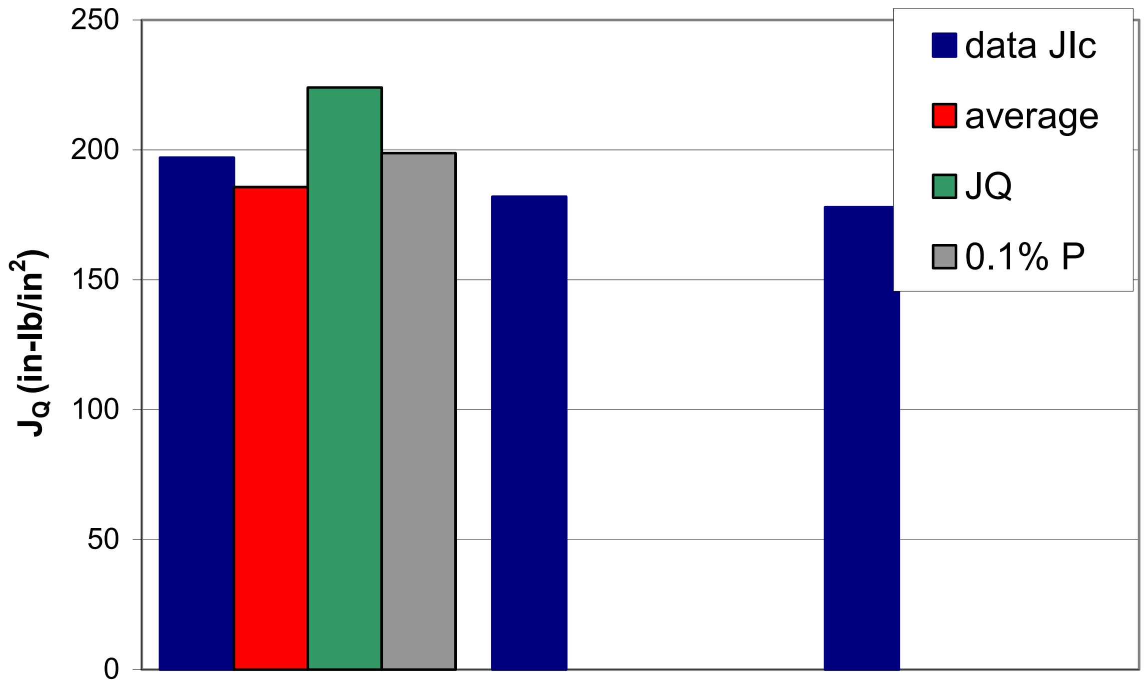

Figure 16a – C1 values for determining J_Q

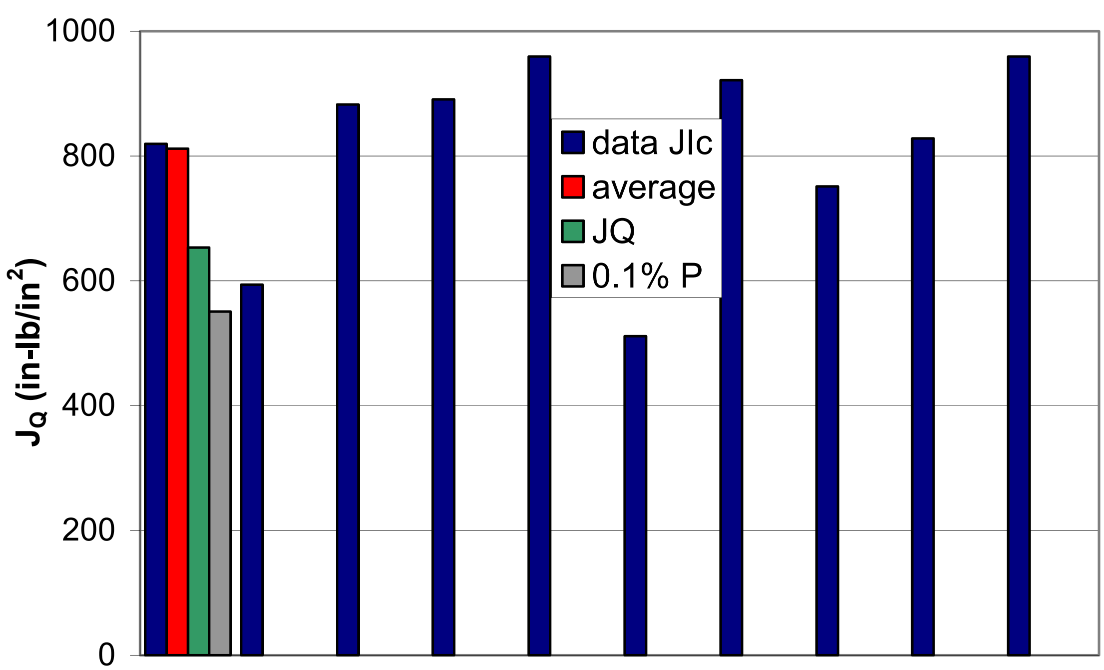

Figure 16b – C2 values for determining J_Q

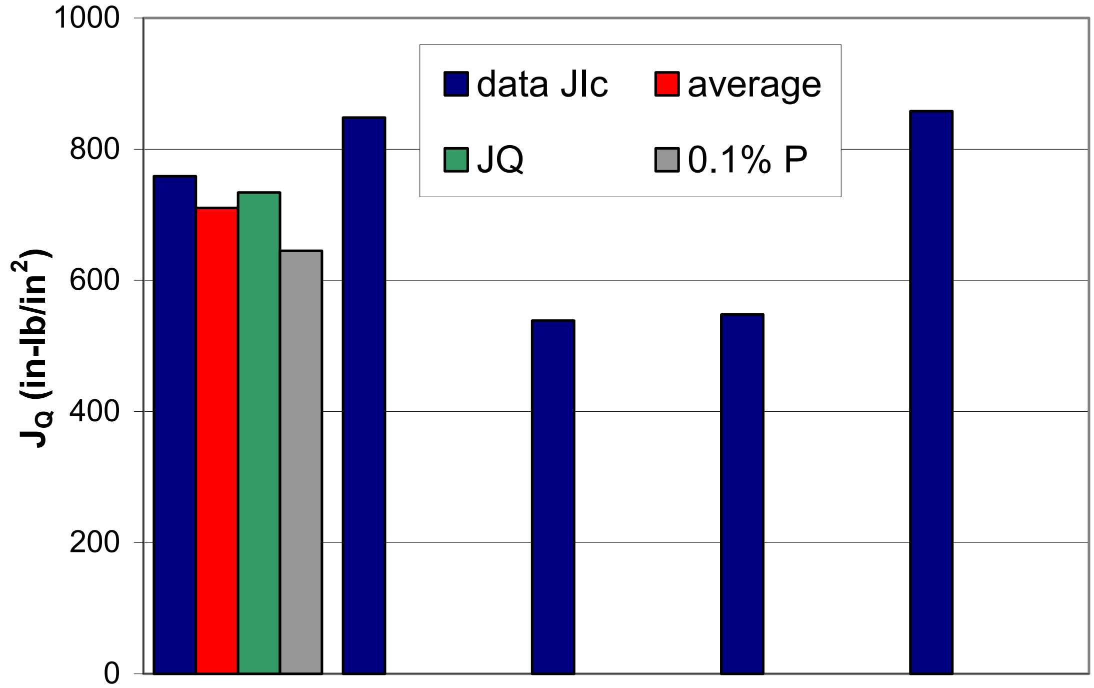

Figure 16c – C3 values for determining J_Q

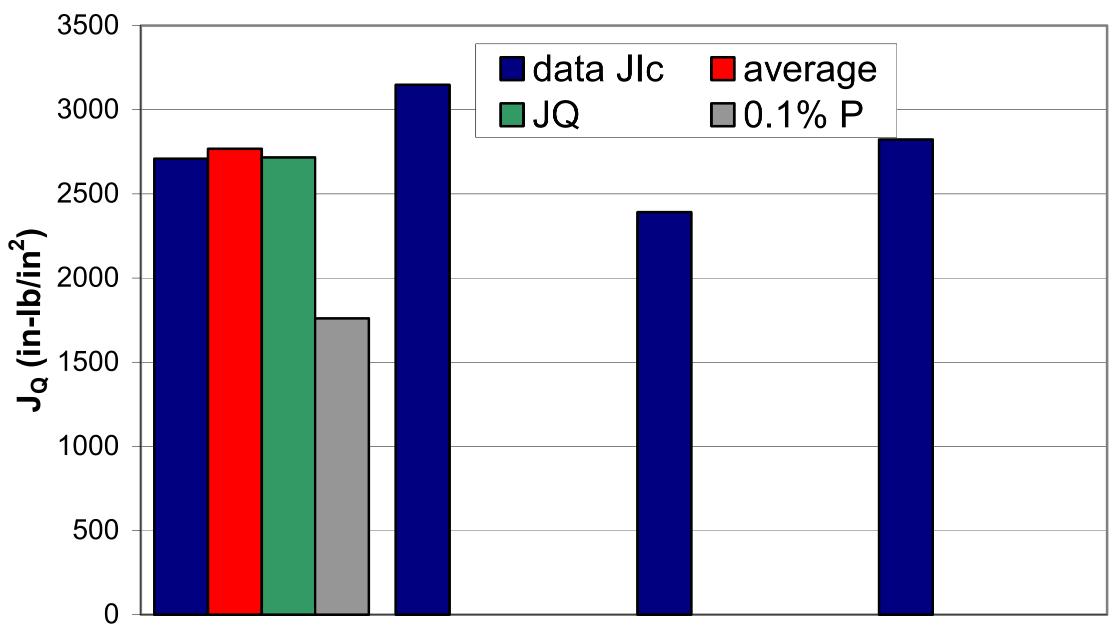

Figure 16d – C4 values for determining J_Q

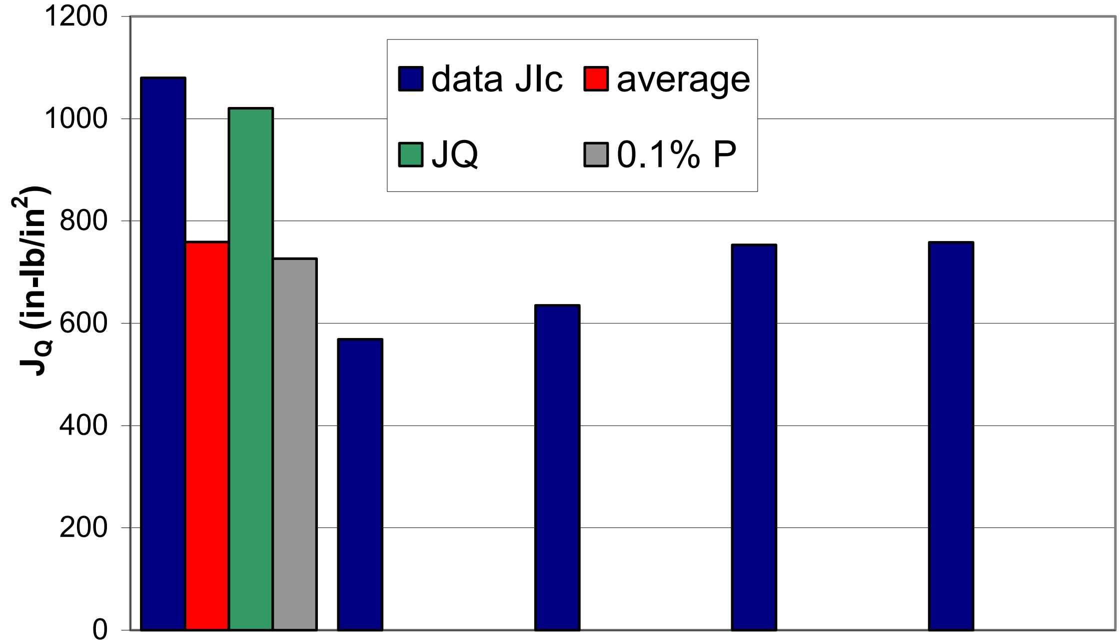

Figure 16e – C5 values for determining J_Q

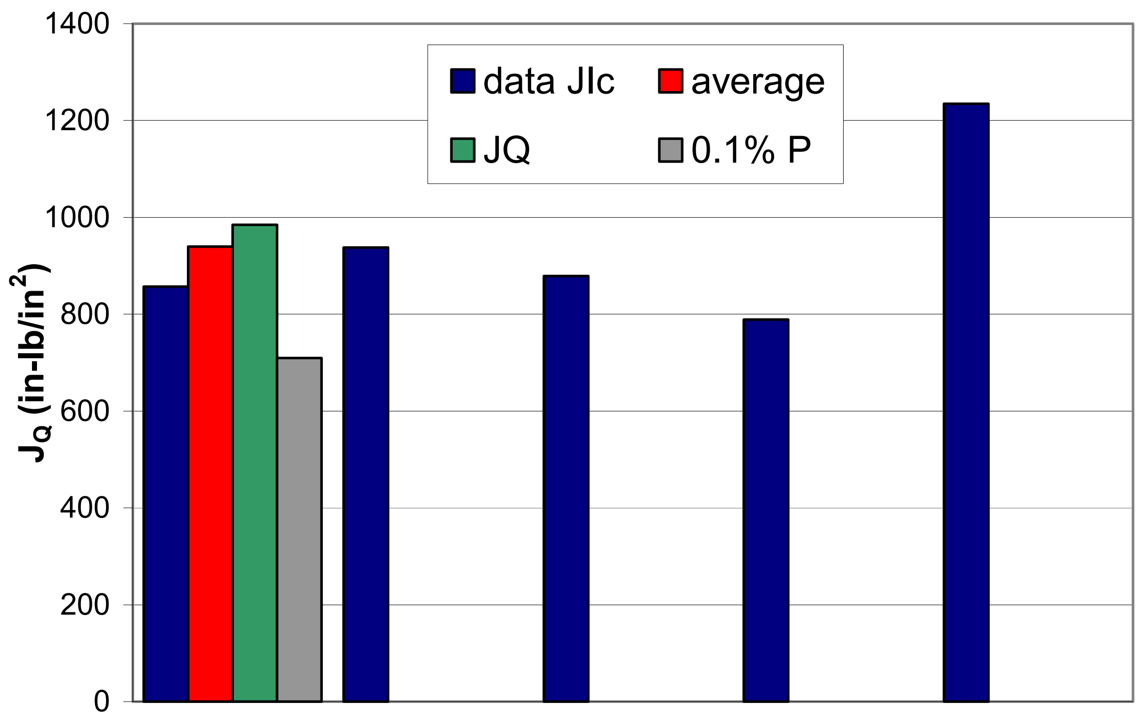

Figure 16f – C6 values for determining J_Q

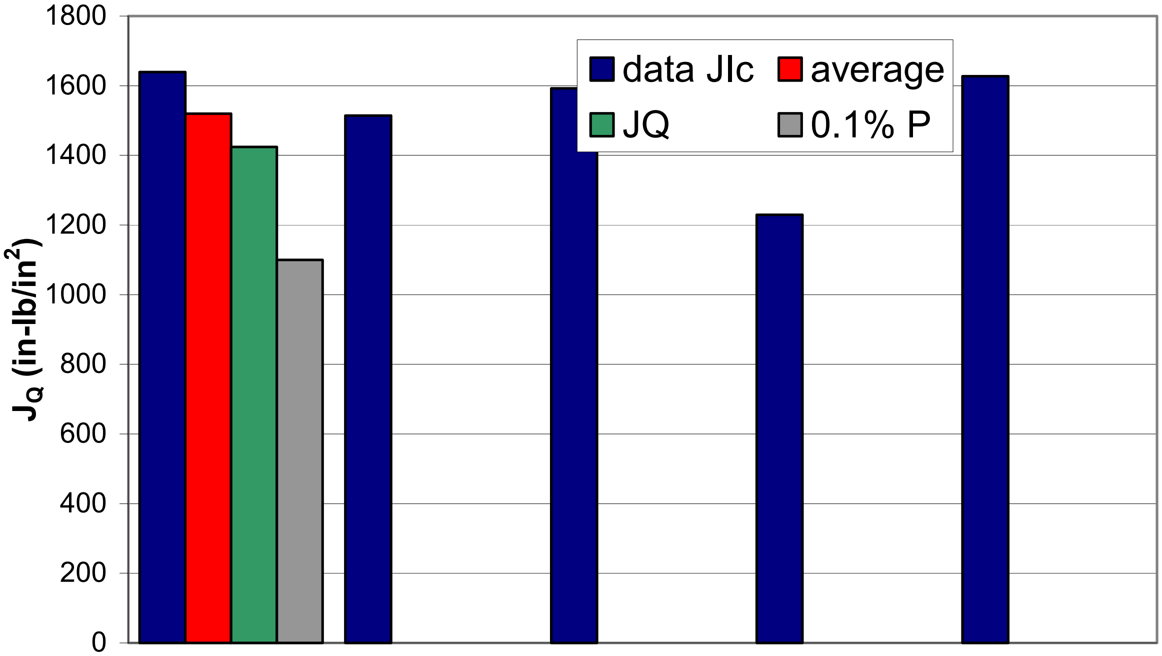

Figure 16g – C7 values for determining J_Q

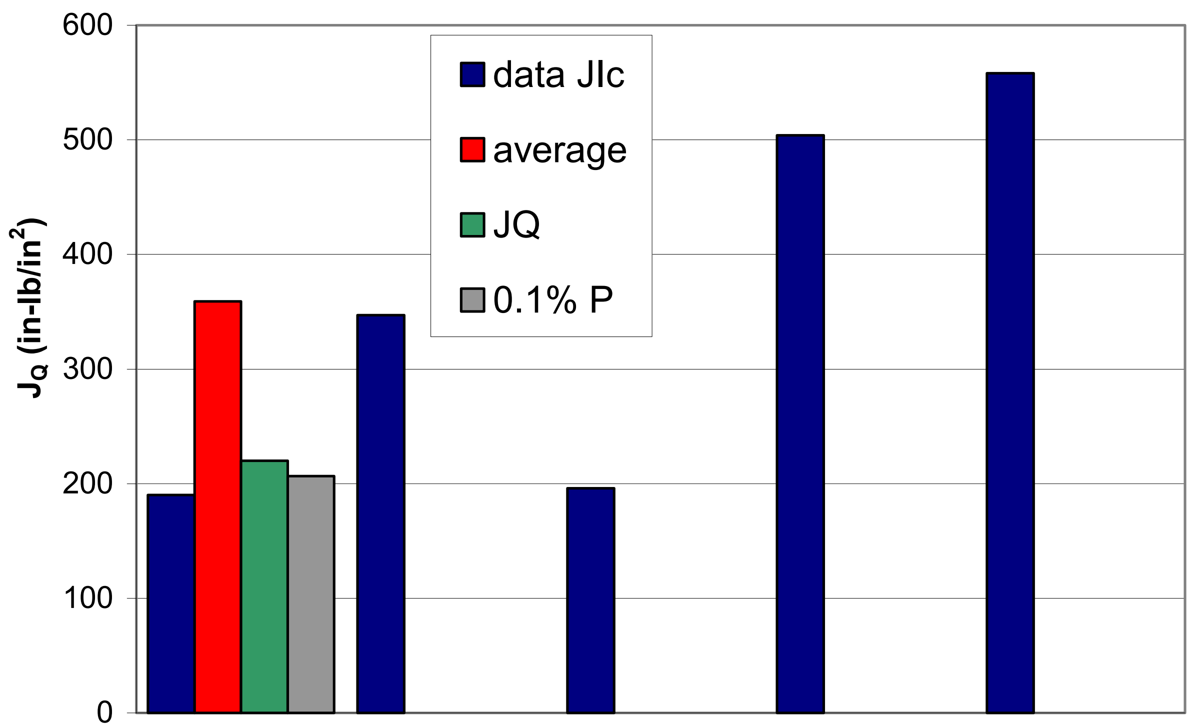

Figure 16h – C8 values for determining J_Q

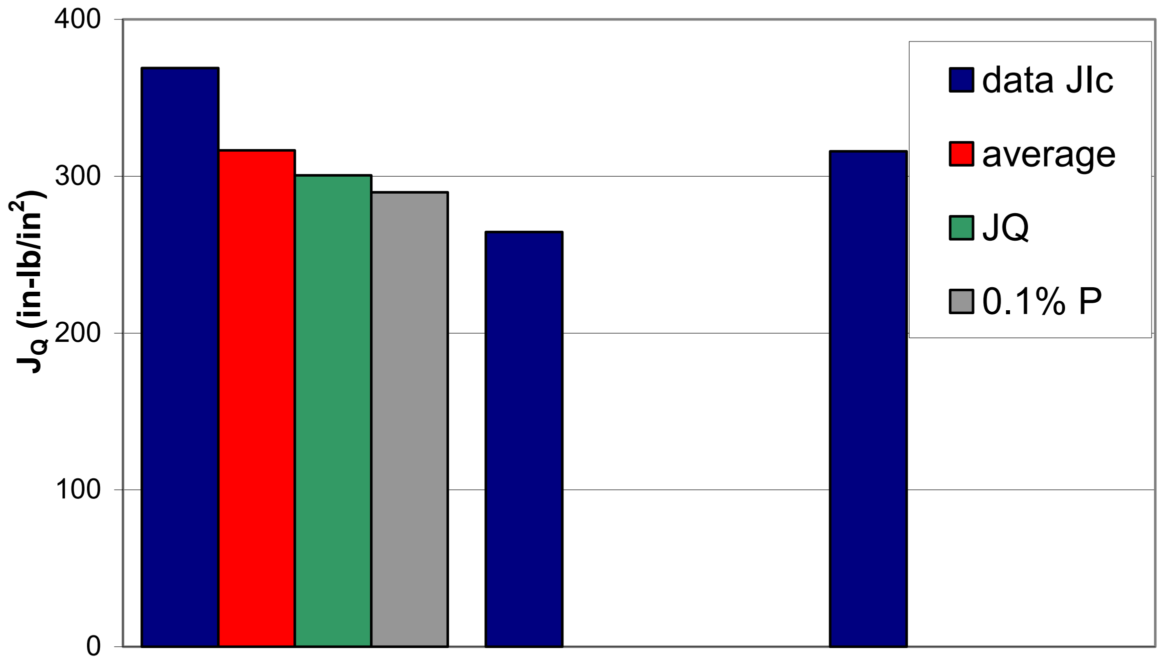

Figure 16i – C9 values for determining J_Q

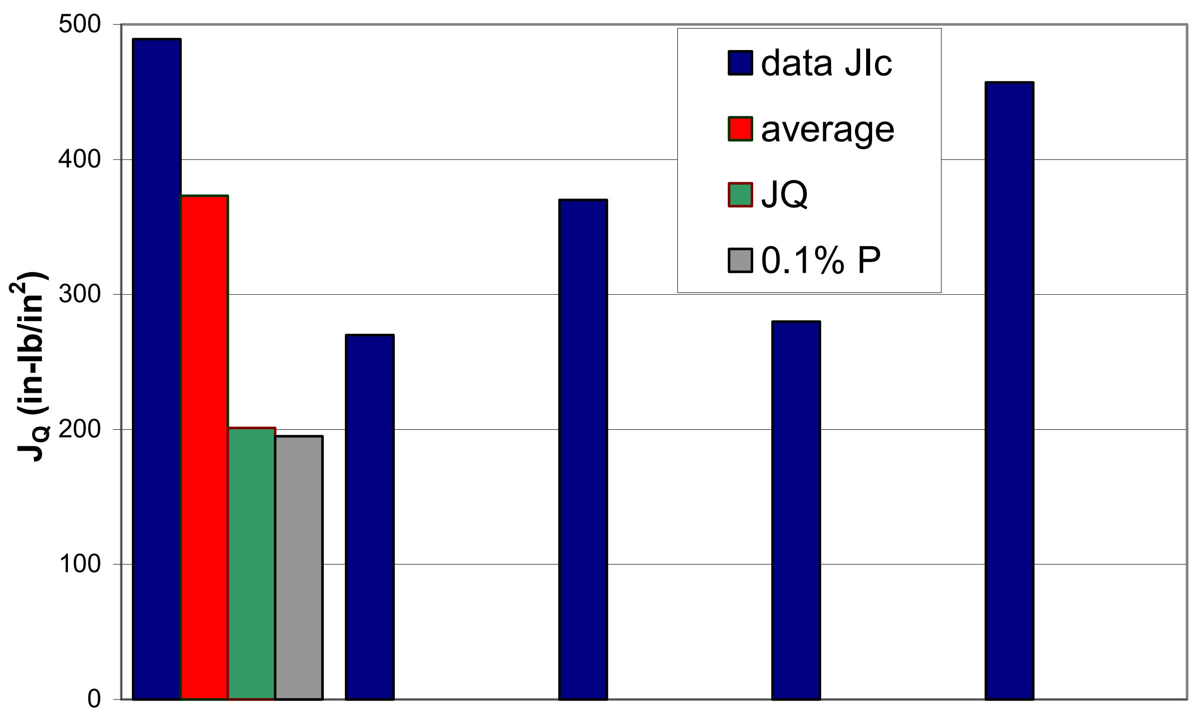

Figure 16j - C10 values for determining J_Q

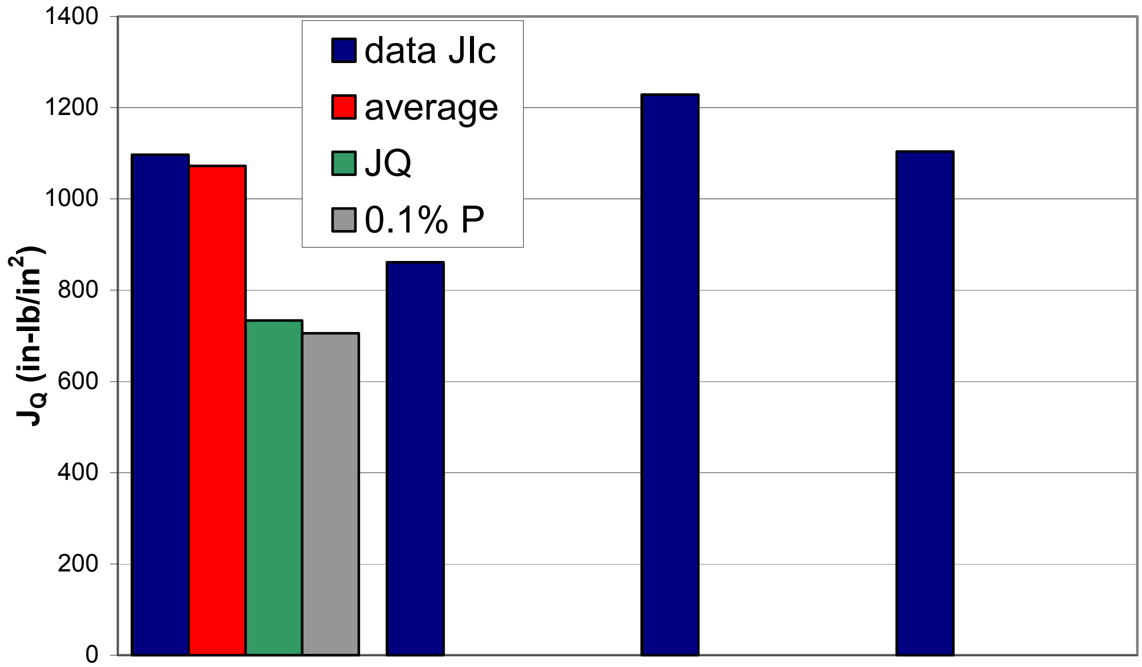

Figure 16k - C11 values for determining J_Q

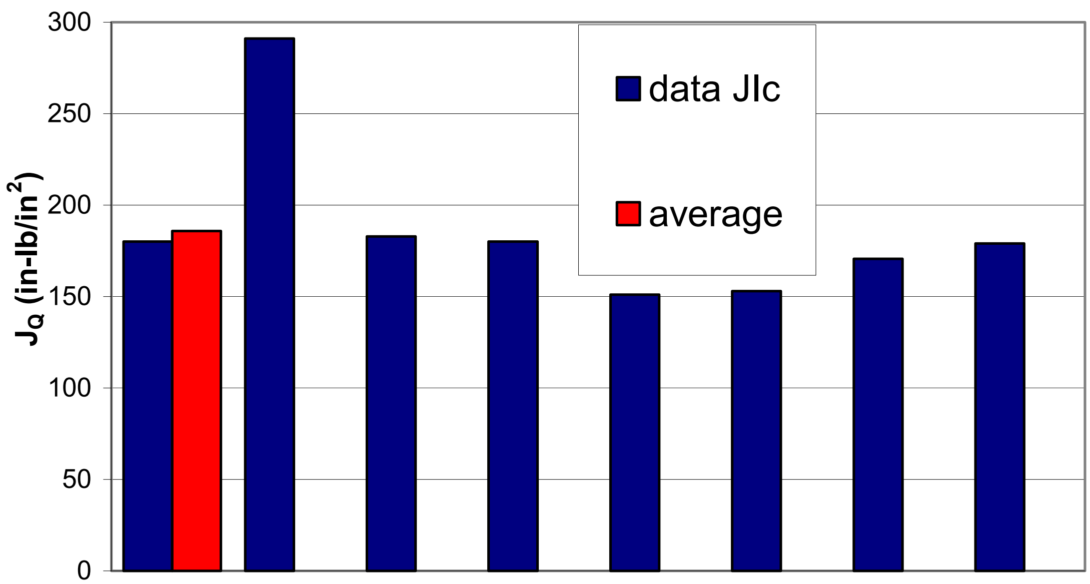

Figure 16l - C12-C16 values for determining J_Q

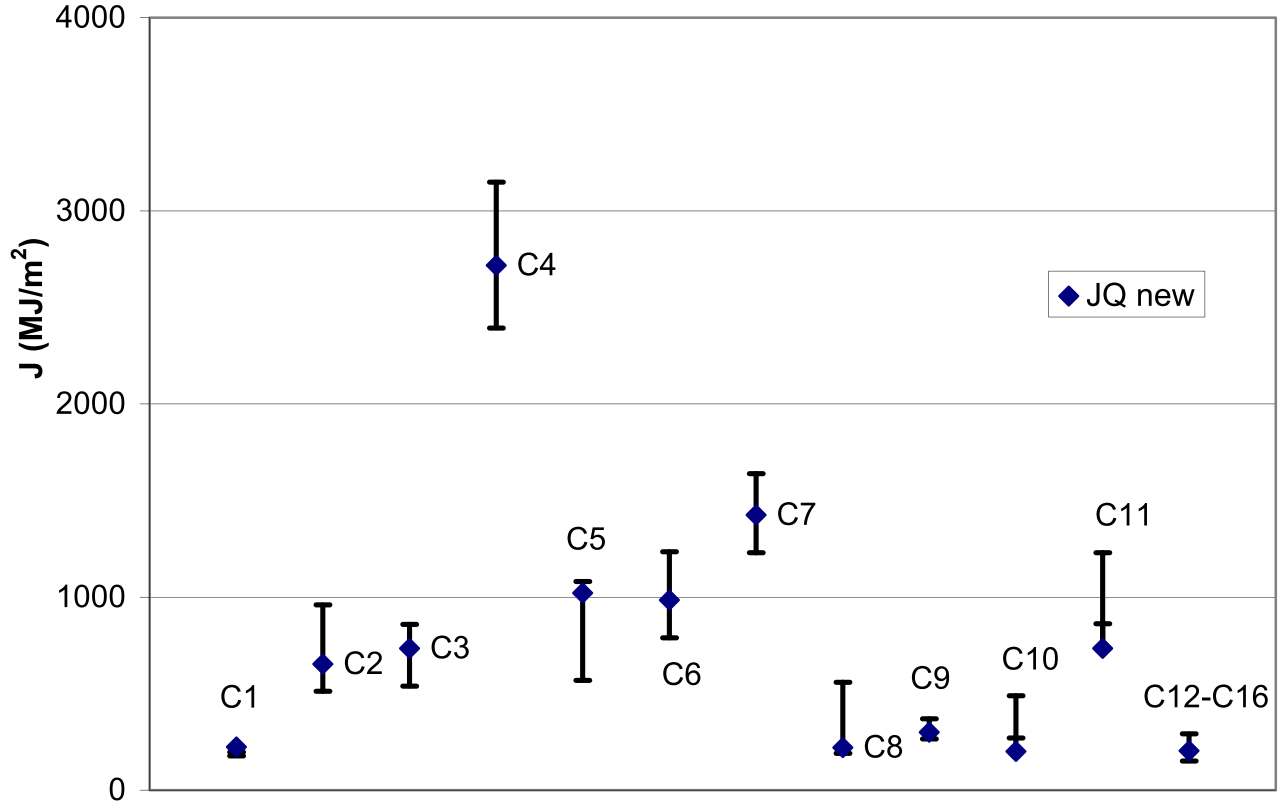

Figure 17 – New J_Q estimation comparison wit error bars for the maximum and minimum values for the J_Q values from other laboratories

Table 1 - Material dimensions for compact specimen tests							
Specimen	**Material**	**W**	**B**	**B_N**	**a_o**	**Δa**	**σ_{flow}**
A1	GKSS	25	12.5	12.5	14,22	2,47	**544.5**
A2	GKSS	25	12.5	12.5	14,29	2,55	**544.5**
A3	GKSS	50	25	25	27,57	4,68	**544.5**
A4	GKSS	50	25	25	27,71	4,59	**544.5**
A5	GKSS	50	25	25	27,46	4,75	**544.5**
A6	GKSS	50	25	25	28,09	2,76	**541.0**
A7	GKSS	50	25	25	28,59	4,77	**541.0**
A8	GKSS	100	50	50	56,98	6,38	**541.0**
A9	GKSS	100	50	50	56,56	9,43	**541.0**
A10	GKSS	100	50	50	56,78	5,09	**544.5**
A11	GKSS	200	100	100	113,15	17,47	**541.0**
A12	GKSS	200	100	100	114,21	8,57	**541.0**
B1	A508	508	254	203.2	298.958	73.00	**465.4**
B2	A509	508	254	203.2	295.275	71.22	**465.4**
B3	A510	50.8	25.4	20.32	26.1874	6.93	**488.9**

* Dimensions in millimeters, Stress in MPa.

Table 2 - Material properties 1						
Specimen	**W (mm)**	**E (GPa)**	σ_{Yield} (MPa)	σ_{UTS} (MPa)	σ_{flow} (MPa)	**Test Temperature (°C)**
A1	25	187.5	470.0	619.0	544.5	0.0
A2	25	173.3	470.0	619.0	544.5	0.0
A3	50	205.2	470.0	619.0	544.5	0.0
A4	50	207.3	470.0	619.0	544.5	0.0
A5	50	203.7	470.0	619.0	544.5	0.0
A6	50	210.2	470.0	612.0	541.0	20.0
A7	50	203.3	470.0	612.0	541.0	20.0
A8	100	210.9	470.0	612.0	541.0	20.0
A9	100	203.8	470.0	612.0	541.0	20.0
A10	100	214.3	470.0	619.0	544.5	0.0
A11	200	207.8	470.0	612.0	541.0	20.0
A12	200	207.1	470.0	612.0	541.0	20.0
B1	508	192.6	386.0	545.0	465.0	-
B2	508	182.8	386.0	545.0	465.0	-
B3	50.8	201.6	386.0	545.0	465.0	-

Table 3 - Material dimensions for test specimens							
Specimen	**Material**	**W**	**B**	**B_N**	**a_o**	**Δa**	**σ_{flow}**
C1	AL	1.992	0.995	0.793	1.201	0.484	52.0
C2	Steel	2.0	1.0	0.8	1.130	0.105	93.0
C3	Steel	2.0	1.0	0.786	1.210	0.543	93.0
C4	Steel	2.0	1.0	0.8	1.224	0.298	84.0
C5	Steel	2.0	1.0	0.8	1.227	0.037	76.0
C6	Steel	2.0	1.0	0.8	1.249	0.077	76.0
C7	Steel	2.0	1.0	0.8	1.240	0.437	76.0
C8	Steel	12.0	6.0	4.8	6.210	3.405	86.4
C9	Steel	2.0	1.0	0.8	1.224	0.028	76.0
C10	Steel	4.0	2.0	1.6	2.056	0.005	85.5
C11	Steel	4.0	2.0	1.6	2.035	0.011	85.5
C12	AL	2.0	1.0	0.8	1.236	0.035	52.0
C13	AL	2.0	1.0	0.8	1.232	0.013	52.0
C14	AL	2.0	1.0	0.8	1.237	0.037	52.0
C15	AL	2.0	1.0	0.8	1.224	0.028	52.0
C16	AL	2.0	1.0	0.8	1.232	0.057	52.0

*Dimensions in inches, Stress in ksi

Table 4 - Material properties 2					
Specimen	**W (in)**	**E (psi)**	**σ_{Yield} (kpsi)**	**σ_{flow} (kpsi)**	**Test Temperature (°C)**
C1	2.0	1.10E+07	44.0	52.0	25.0
C2	2.0	2.90E+07	83.0	93.0	25.0
C3	2.0	2.90E+07	83.0	93.0	25.0
C4	2.0	2.90E+07	76.0	84.0	25.0
C5	2.0	2.90E+07	65.0	76.0	-15.0
C6	2.0	2.90E+07	65.0	76.0	-2.0
C7	2.0	2.90E+07	65.0	76.0	23.0
C8	12.0	2.90E+07	68.8	86.4	82.0
C9	2.0	2.90E+07	65.0	76.0	-31.0
C10	4.0	2.90E+07	72.0	85.5	12.0
C11	4.0	2.90E+07	72.0	85.5	12.0
C12	2.0	1.10E+07	45.0	52.0	25.0
C13	2.0	1.10E+07	45.0	52.0	25.0
C14	2.0	1.10E+07	45.0	52.0	25.0
C15	2.0	1.10E+07	45.0	52.0	25.0
C16	2.0	1.10E+07	45.0	52.0	25.0

Table 5 - J_Q Values for different methods and laboratories 1							
		NEW ANALYSIS			ASTM		
Specimen	**W (mm)**	**$J_{Q\ new}$**	**$J_{Q\ 0.995\%\ P}$**	**$J_{Q\ 0.99\%\ P}$**	**J_Q**		**Rsc**
A1	25	0.778416	0.666701	0.577679	0.657240	MJ/m^2	2.3806
A2	25	0.616101	0.616101	0.550081	0.633854	MJ/m^2	2.3286
A3	50	0.829651	0.706431	0.629709	0.813028	MJ/m^2	2.2446
A4	50	0.904273	0.801623	0.705730	0.991699	MJ/m^2	2.3806
A5	50	0.894291	0.794894	0.726585	0.955348	MJ/m^2	2.2706
A6	50	0.972451	0.744227	0.682015	0.695963	MJ/m^2	2.2289
A7	50	0.901181	0.815943	0.725302	0.868390	MJ/m^2	2.2504
A8	100	1.014811	0.895133	0.812397	1.495468	MJ/m^2	2.2670
A9	100	0.955696	0.860522	0.789024	1.065560	MJ/m^2	2.2518
A10	100	1.059944	0.801028	0.748705	1.215961	MJ/m^2	2.2473
A11	200	1.250026	0.997778	0.884532	-	MJ/m^2	2.2234
A12	200	0.954769	0.936153	0.767759	-	MJ/m^2	2.2670
B1	508	0.166522	0.140159	0.140159	-	MJ/m^2	1.8015
B2	508	0.163014	0.125977	0.125977	-	MJ/m^2	1.7479
B3	50.8	0.183918	0.146356	0.113295	0.141530	MJ/m^2	1.7773

Table 6 - J_Q Values for different methods and laboratories 2								
		NEW ANALYSIS			OTHER LABS DATA			
Specimen	**W**	**$J_{Q\ new}$**	**$J_{Q\ 0.995\%\ P}$**	**$J_{Q\ 0.99\%\ P}$**	**$J_{Q\ max}$**	**$J_{Q\ min}$**	**$J_{Q\ ave}$**	**Rsc**
C1	2.0	224.1	210.0	198.8	197.0	178.0	185.7	1.4518
C2	2.0	653.1	554.4	512.5	959.5	511.4	811.8	1.9665
C3	2.0	733.9	664.2	645.1	857.7	538.6	710.2	2.0981
C4	2.0	2717.1	2224.6	1760.1	3148.0	2392.0	2768.5	2.1904
C5	2.0	1020.7	314.0	726.5	1080.0	569.0	759.1	2.1450
C6	2.0	985.0	804.4	709.9	1235.0	789.0	939.6	2.0907
C7	2.0	1424.2	1203.5	1100.2	1639.0	1229.0	1520.2	2.1795
C8	12.0	220.1	213.9	206.5	558.0	190.0	359.0	1.0710
C9	2.0	300.6	289.7	289.7	369.0	264.4	316.4	1.9197
C10	4.0	201.0	199.6	195.0	489.0	270.0	373.2	1.3804
C11	4.0	733.3	718.3	706.0	1229.0	861.0	1072.8	1.9109
C12	2.0	204.2	185.4	180.7	-	-	-	1.3621
C13	2.0	170.5	166.2	161.9	-	-	-	1.3188
C14	2.0	213.5	194.9	175.4	-	-	-	1.3274
C15	2.0	181.2	171.8	158.8	-	-	-	1.3071
C16	2.0	211.2	182.2	177.5	-	-	-	1.3247
C15-C19	2.0	204.2	-	-	291.0	151.0	185.9	-

*Units for J in-lb/in^2, W units Inches

APPENDIX B

A MATLAB program to simultaneously solve for constants for the M and N calculations used in the LMN calculations. Program uses Microsoft Excel spread sheet to get values used in solver and writes calculated values into spreadsheet columns and rows.

```
% Calculates the LMN coefficients
clear all
clc
format long;

c=ddeinit('excel','A508.1 LMN.xls');% input file name here and below also
dc=ddereq(c , 'r4c18:r393c18'); % reads data from Column " U " r4c21:r###c21
m=ddereq(c , 'r4c19:r393c19'); % reads data from Column " V " r4c22:r###c22
n=ddereq(c , 'r4c20:r393c20'); % reads data from Column " W " r4c23:r###c23

nf=23; % Last row in data
for i=2:22;

   a=[m(i), n(i) ; m(nf), n(nf)];
   b=[dc(i), dc(nf)];
   x=b*inv(a)';
   mm(i)=x(1);
   nn(i)=x(2);
   i=i+1;

end

c=ddeinit('excel','A508.1 LMN.xls');
ddc=ddepoke(c,'r4c21:r407c21',mm'); % writes data to Column " X " r4c24:r###c24
dcc=ddepoke(c ,'r4c22:r407c22',nn'); % writes data to Column " Y " r4c25:r###c25
```

VITA

Brandon Pehrson was born on April 26, 1977, in Phoenix Arizona. He graduated from Del Norte High school in 1995. He attended the University of New Mexico for a year studying Mechanical engineering. After returning from a mission to Portugal from 1996 to 1998 he attended Pellissippi State Community College in Tennessee. He attended Pellissippi State Community College studying engineering basics and machining technology. He started at the University of Tennessee in 1999 and graduated in May 2004 with bachelor's degrees in Aerospace engineering and Mechanical engineering. In the summer of 2004 he started graduate school. He was awarded a graduated assistantship in August of 2004. In graduate school he studied Mechanical engineering. This degree will be awarded in May 2005.