NEW METHODS FOR CHARACTERIZING FRACTURE TOUGHNESS BEHAVIOR

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ABSTRACT

New developments in the fracture mechanics approach for characterizing the fracture behavior of structural components are discussed. This includes both the test methods used to obtain the material property labeled fracture toughness and the application methodologies used to predict the behavior of structural components. For the test methods new approaches to characterizing the toughness of steels in the transition region have been developed and are being standardized. This method uses Weibull statistics to handle the scatter in transition toughness and a master curve to predict the temperature dependence. Also the test methods are being combined to create a more complete and versatile approach to fracture toughness testing. For the applications side several new modeling approaches have been developed to allow the fracture prediction to be conducted with simple hand calculations. These include a model to predict the transition behavior of steel component models from the toughness results of a test specimen and a model to predict the ductile fracture behavior in terms of a load versus displacement behavior from the same result on a test specimen. This prediction has been shown to work well for both ductile metals and nonmetal components.

KEYWORDS

Fracture toughness, structural components, ductile fracture, transition fracture, models, statistics, deformation behavior, standard tests

INTRODUCTION

Fracture mechanics methods are used to assure the reliability and safety of critical structural components. For this approach a material property labeled fracture toughness is measured on a laboratory type specimen. This property is then used to assess the fracture potential of a component geometry. The important steps in the predictive procedure are the measurement of the fracture toughness property and the transference of the result to the structural component geometry. This approach has been successfully applied for many years for certain types of behavior.

The first application of the fracture mechanics approach was for materials which behaved in a strictly linear elastic manner. The parameter K, crack tip stress intensity factor, (Irwin, 1957, Paris and Sih, 1965) was used to measure toughness and to make the prediction of potential component fracture. This approach applied to only the very high strength and most brittle materials and did not cover many engineering applications where materials were usually designed to yield before failing. To apply the fracture mechanics method to materials more realistically used in engineering applications the nonlinear fracture parameters J (Rice, 1968, Begley and Landes, 1972) and CTOD (Wells, 1961, Dawes, 1979) were developed. For these parameters materials which exhibited nonlinear plastic behavior before failing could be tested and the results used to apply to the structural components (Kumar et al, 1981, Burdekin and Dawes, 1991).

With these new parameters, test methods and application schemes the fracture mechanics approach for characterizing the fracture behavior of structural components applied to a wider range of materials. The extremes of fracture behavior were well covered, the very brittle and the ductile. However, the intermediate behaviors were not so well characterized. In particular the fracture toughness behavior of steels in the transition region were not well characterized. For this the extensive scatter and size and geometry effects left the measurement and application of the fracture mechanics approach in considerable doubt (Milne and Chell, 1976, Landes and Shaffer, 1980). New methods for measuring the toughness using the J parameter as well as the CTOD have been developed and standardized and Weibull statistics are used to handle the scatter. Also, the standard test methods for characterizing the fracture toughness behavior has been made more versatile by the development of unified test standards which allows all types of fracture behavior and the choice of fracture parameter to be used for characterizing toughness in a single test standard.

Along with the development of the new standard fracture toughness tests, work is in progress to streamline the testing. An approach called normalization allows the R curve fracture toughness to be measured without the use of an on-line crack monitor (Landes and Herrera, 1988, Landes et al, 1991). This procedure can be used for tests in which the conditions are difficult and not all parameters can be measured (Lee and Landes, 1993 and 1994). This approach can be useful for tests conducted at high temperature, under harsh environmental conditions or in a hot cell. Also, this procedure would be useful for tests conducted at high loading rates where traditional crack length measurement techniques cannot be used.

The ultimate objective of the fracture mechanics approach is the application of the test results to the prediction of fracture behavior in structural components. This use of the test data has often been difficult because some of the toughness measurements showed size, thickness and geometry effects. Recent work has shown that the traditional one parameter approach to fracture characterization does not work when the toughness results are applied to component geometries that are much different from the test specimen geometry (Anderson and Dodds, 1991, Hancock et al, 1993, O'Dowd and Shih, 1991 and 1992). The size and geometry effects, labeled constraint, affect the application of the fracture toughness significantly. The traditional one parameter approaches assumes that the dominant term in the crack tip stress field controls the fracture toughness behavior. This has been found to be true only for the extremes of high strength and low toughness materials, essentially materials that cannot be used for engineering applications. A two parameter approach that uses the second term in the crack tip stress field series as a fracture toughness characterizing parameter is now used to handle the constraints effects that are encountered in the transference of the test data to structural components. The most popular two parameter approaches are the K and T parameters for essential linear elastic behavior (Hancock, 1993) and the J and Q for nonlinear behavior O'Dowd and Shih, 1993, Dodds et al, 1993). The application of the two parameter approaches has been to use them as correlating parameters. A locus of toughness points is measured as a function of the two parameters and this locus is used to predict the behavior of the structure at the same corresponding point of the two parameters (Shih et al, 1993). Recent results have shown that a fracture locus may in itself have geometry dependence and the correlating approach should not be used (Landes, 1995). Rather the two parameters should be used with models which predict the fracture behavior as a result of a fracture mechanism. This has been done, for example, using a model with a weak link triggering mechanism for brittle fracture (Landes, 1996) or by numerically modeling stable crack extension through faulted material for ductile fracture (Xia and Shih, 1996).

For ductile fracture behavior the deformation behavior of the structure is likely to play and important role in the failure of the structural component model. A method which can transfer the results of a typical fracture toughness test geometry directly to the structural component has been developed for this ductile behavior (Landes et al, 1993). In this paper some new developments in the testing for fracture toughness and application of results through fracture models will be presented. This discussion will first cover the new approaches for testing and applying fracture toughness in the transition for steels and second will discuss some of the new testing procedures and application models for ductile fracture behavior .

TRANSITION FRACTURE

The new approaches to fracture toughness testing allow a measurement of toughness in the transition for steels with a statistical analysis of the resulting toughness values to handle scatter. The test is conducted with the J parameter and a value of toughness J_c is measured at a point of unstable fracture. The J_c values are converted to equivalent K_{Jc} values with the plane stress expression

$$K_{Jc} = \sqrt{J_c E} \tag{1}$$

where E is the elastic modulus. Testing in the transition always results in a toughness data set that has extensive scatter and size and geometry effects. The new test method uses a Weibull statistical model with three parameters given by

$$P = 1 - \exp\left[-\left(\frac{K_{Jc} - 20}{K_o - 20}\right)^4 \right] \tag{2}$$

where P is the probability that a specimen fails at or below toughness K_{Jc}, a Weibull slope of 4 is chosen and the lower limit of the statistical distribution is 20 $MPa\sqrt{m}$. The only parameter that is fit to the data is the scale parameter, K_o. From this model a size correction to adjust the toughness results from that of the test specimen size to a standard unit size is given by

$$K_{Jc(1)} = 20 + (K_{Jc(x)} - 20)\left(\frac{B_{(x)}}{B_{(1)}}\right) \tag{3}$$

where $B_{(x)}$ and $B_{(1)}$ are the thicknesses for the test size and the unit size respectively of two proportionally sized specimens. $K_{Jc(x)}$ is the measured toughness on specimen size $B_{(x)}$ and $K_{Jc(1)}$ is the toughness adjusted to unit size, $B_{(1)}$; all toughness values are in units $MPa\sqrt{m}$. After making the size adjustment, the three parameter Weibull fit can be analyzed to get the median value for the distribution which occurs at 50 percent probability, P. The median values are then given a relationship that accounts for the temperature effect throughout the transition by fitting a master curve to the plot of median toughness versus temperature (Wallin, 1993). The master curve equation in the method was developed by McCabe (1996) and is given by

$$K_{Jc(med)} = 30 + 70 \exp[0.019(T - T_o)] \tag{4}$$

where $K_{Jc(med)}$ is the median toughness of a distribution as obtained from the distribution in eq. 2, T is the test temperature in °C and T_o is the reference temperature.

Using the Weibull fit with adjustment to unit size and the master curve takes care of size and temperature effects in the transition. However, the results can only be used to predict the behavior of the same test specimen geometry type. An additional concern is the effect of geometry. The structural component geometry may not have the same distribution of toughness values as the test geometry. A usual approach is to try to correlate the geometry effects with the two parameter fracture toughness locus; an example of this where the fracture locus is given in terms of J and Q is shown in Fig 1 (Shih et al, 1993). However, it has been suggested that the J-Q fracture locus may also have a geometry dependence as shown in Fig. 2 (Landes 1995). The only way to deal with the geometry effects in the transition seems to be to use a mechanistic approach where a crack tip model with a local failure criterion is used. If the transition fracture is predominately stress controlled, as has often been suggested, a model based on crack tip stresses is needed.

A simple model, based on the assumption that fracture is caused when a triggering weak link reaches a characteristic stress value, labeled cleavage stress, has been used to predict the transition fracture toughness distribution for tension panels with central and edge through cracks and with surface flaws (Landes 1995 and 1996). The input to the model is a set of toughness results that have been measured on a test specimen. Using the concept of a cleavage stress needed to trigger fracture as given by Heerens, et al, (1989) the model uses a crack tip stress fields that has been numerically characterized with large strain theory (O'Dowd and Shih, 1991 and 1992, Dodds et, al, 1993) to determine crack tip stress fields. These crack tip stresses are affected by the constraint parameters, for example, the J and Q parameters for nonlinear deformation. A schematic picture of the model is given in Fig. 3. Combining the cleavage stress and the crack tip stresses with the measured toughness values, these being a scatter band of toughness values, a set of weak link distances are determined. The weak link distances are considered to be invariant with geometry and temperature and form a set of material properties. Also the cleavage stress is considered to be invariant with geometry and temperature. Using these properties, weak link distances and cleavage stress, a prediction of a toughness scatterband for a new temperature or a new geometry can be made. For this the J and Q variation are needed in the new geometry. Fig. 4 shows the prediction of the transition temperature behavior of a 20MnMoNi55 steel using the model. Starting with input toughness data from compact specimen tests C(T) predictions of the scatterband of toughness values are given for tension panels with through central cracks, M(T), and through edge cracks DE(T) in Fig. 5 and for tension panels with surface flaws in Fig. 6. The predictions are made for the high, low and median values of toughness so that a scatterband can be drawn. For the M(T) and DE(T) experimental measurements of toughness were made and are plotted on Fig. 5 for comparison with the predictions. The surface flaws have no experimental measurements of toughness for this material.

DUCTILE FRACTURE

Ductile fracture toughness characterization is done with a crack growth resistance curve or R curve. In this the fracture parameter is plotted as a function of the ductile crack extension. The test method for developing this has been standardized for nearly a decade. The difficulty with the R curve test is that an on-line crack length monitor is needed to develop the crack length data used for the crack extension measurement. The present standard methods often give some variability in this measurement that has made the procedure difficult. A new combined J standard allows the an alignment of the initial portion of the R curve so that initiation toughness values can be evaluated from the R curve. In addition, new methods called normalization can make the crack length measurement from the plastic deformation characteristics of the test record (Landes and Herrera, 1988, and Landes et al, 1991). With the normalization procedure the three main variables during the test, load, displacement and crack length are functionally related. Therefore, knowing two of these variables, the third is specified by the functions. For example, given load and displacement values the crack length is specified. This procedure is useful for developing some procedures for difficult testing condition such as severe environments, high temperature and irradiated materials. Here the displacement need not be explicitly measured and the R curve is developed from only the load versus crack length measurements (Lee and Landes, 1993 and 1994).

The same relationships that lead to the normalization procedure can be used as an application approach. From the test result of a laboratory test specimen the load and displacement behavior of a structural component geometry can be predicted by a set of analysis steps that includes the normalization procedure as part of the analysis, Fig. 7, (Landes et al, 1993). The load versus displacement record from a test geometry is separated into a deformation curve and a toughness curve. The deformation curve contains the information about the strength of the material and the hardening characteristics. The toughness contains the information about the crack extension characteristics of the material. What is needed is the same information for the structural geometry. A transformation procedure is used to develop the deformation properties of the structural component. A similar procedure is needed for the toughness behavior. Geometry effects on the R curve behavior make this difficult; however, numerical work on faulted material allows the R curve toughness behavior to be predicted with some good success (Xia and Shih, 1996). Given the deformation and toughness curves for the component geometry, a recombination, like the normalization procedure in reverse, predicts the load and displacement behavior of the component geometry.

The procedure is based on the load separation principle where the load is represented by separable functions $G(a/W)$ and $H(v_p/W)$

$$P = G(a/W)\, H(v_p/W) \qquad (5)$$

The step of transferring the deformation property from the test specimen to the component has undergone some improvements. The original transformation (Zhou, 1992) used a graphical procedure involving limit loads and elastic compliance. A recent analysis, called the common format approach, which showed that all deformation properties can be derived from the stress-strain properties of the material, made this step easier (Donoso and Landes, 1995). Using the common format approach with a set of conversion functions allows this transformation to be made with two simple analytical steps (Cruz and Landes, 1997). For this procedure two conversion factors, f, which is the ratio of the limit loads, P_L between the structure and the test specimen, where P_L is divided by the G of eq. 6 and subscript s represents the structure

$$f = \frac{P_{Ls}/G_s}{P_L/G} \qquad (6)$$

and q, which is the ratio of the normalized elastic displacements at the limit load, V_e,

$$q = \frac{(V_e/W)}{(V_e/W)_s} \qquad (7)$$

give the conversion of the deformation curve from that for the specimen to that of the structure. A simple application of the method can take the load versus displacement for a test specimen and transfer it to predict the load versus displacement behavior for a structure.

Some examples of the application of the method are illustrated for component models. Starting with a load versus displacement curve from a laboratory test the same is predicted for a tension panel with a central crack in Fig. 8. The results of a test are included in this Fig. for comparison. Fig. 9 shows the prediction for a pipe with a circumferential through crack loaded in bending. Again the results of a test are included for comparison.

SUMMARY

New methods for testing and applying fracture toughness results have developed simplified methods for predicting the integrity and safety of structural components. In particular the difficult transition region for steels has a new standard test method that uses Weibull statistics to handle the scatter and size effects encountered in the toughness characterization and a master curve to handle the temperature effects. A model based on the two parameter fracture approach, J and Q, allows this data to be used for predicating the fracture behavior in other structural component models. For the ductile fracture behavior new methods based on normalization allows the load versus displacement behavior for a structural component to be predicted from that of a laboratory test specimen.

REFERENCES

Anderson, T. L. and Dodds, R. H.(1991) "Specimen Size Requirements for Fracture Testing in the Transition Region", Journal of Testing and Evaluation, JTEVA, American Society for Testing and Materials, Philadelphia, Vol. 19, pp. 123-134

Begley, J. A and Landes J. D.,(1972) "The J Integral as a Fracture Criterion," Fracture Toughness, Proceedings of the 1971 National Symposium on Fracture Mechanics, Part II, ASTM STP 514, pp. 1-20.

Burdekin , F. M. and Dawes, M. G.(1991) "Practical Use of Linear Elastic and Yielding Fracture Mechanics with Particular Reference to Pressure Vessels" Proceedings of the Mechanical Engineers Conference, London, May, pp. 28 - 37.

Cruz, J. R. B. and Landes, J. D. (1997) "A Simplified Transformation Approach to Obtain Structural Calibration Functions", (submitted to the 29th National Symposium on Fatigue and Fracture Mechanics)

Dawes, M. G.(1979) "Elastic-Plastic Fracture Toughness Based on CTOD and J-Contour Integral Concepts" Elastic-Plastic, Fracture, ASTM STP 668, J. D. Landes, J. A. Begley and G. A. Clarke, Eds, ASTM, pp. 307-333.

Dodds, R. H., Jr. , Shih, C.F. , and Anderson, T. L. (1993) "Continuum and Micromechanics Treatment of Constraint in Fracture", International Journal of Fracture, Vol. 64, 1993, pp. 101 - 133.

Donoso, J. R. and Landes, J. D. (1994) "Common Format for Developing Calibration Curves in Elastic-Plastic Fracture Mechanics", Engineering Fracture Mechanics, Vol. 47, No. 5, pp. 619-628.

Hancock, J. W., Reuter, W. G., and Parks, D. M. (1993) "Constraint and Toughness Parameterized by T", Constraint Effects in Fracture, ASTM STP 1171, E. M. Hackett, et. al. Eds., American Society for Testing and Materials, Philadelphia, pp. 21-40.

Heerens, J., Read, D. T., Cornec, A. and Schwalbe, K-H. (1989) "Interpretation of Fracture Toughness is the Ductile-to-Brittle Region by Fractographic Observations" Defect Assessment in Components - Fundamentals and Applications, ESIS/EGF 9, (Eds. J. G. Blauel and K.-H. Schwalbe), Mechanical Engr. Publications, London, pp. 659-678.

Irwin, G. R. (1957) "Analysis of Stresses and Strains Near the End of a Crack Traversing a Plate", Journal of Applied Mechanics, Trans ASME, Vol. 24, pp. 361-364.

Kumar, V., German, M. D., and Shih, C. F. (1981) "An Engineering Approach for Elastic Plastic Fracture Analysis," NP 1931, EPRI Project 1237-1, July.

Landes, J. D. (1995) "Application of a J-Q Model for Fracture in the Ductile-Brittle Transition" presented at the 27th National Symposium on Fatigue and Fracture Mechanics, Williamsburg, VA, June.

Landes, J. D. (1996) " A J-Q Model for Predicting Fracture in the Ductile-Brittle Transition", Fatigue and Fracture of Engr Materials and Structures, Vol. 19, No. 7, pp. 869-877.

Landes, J. D. and Herrera, R. (1988) "A Direct J-R Curve Analysis of Fracture Toughness Tests," (with R. Herrera), Journal of Testing and Evaluation JTEVA, Vol. 16, No. 5, September, pp. 427-449.

Landes, J. D., Zhou, Z. and Brown, K. H.(1993) "An Application Methodology for Ductile Fracture Mechanics", Fracture Mechanics: Twenty-Third Symposium, ASTM STP 1189, Ravinder Chona, Ed, ASTM, pp. 229-264.

Landes. J. D., Zhou, Z., Lee, K., and Herrera, R.(1991) "Normalization Method for Developing J-R Curves with the LMN Function", Journal of Testing and Evaluation, JTEVA, Vol 19, No 4, July, pp. 305-311.

Landes, J. D. and Schaffer, D. H.(1980)"Statistical Characterization of Fracture in the Transition Region,", Fracture Mechanics Twelfth Conference, ASTM STP 700, American Society for Testing and Materials, pp. 368-382.

Lee, K and Landes J. D.,(1993) "Developing J-R Curves Without Displacement Measurement Using Normalization", Fracture Mechanics: Twenty-Third Symposium, ASTM STP 1189, Ravinder Chona, Ed, ASTM, pp. 113-167

Lee, K and Landes, J. D.(1994) "A New Application of Normalization: Developing J-R Curves from Displacement versus Crack Length and Displacement Alone", Fracture Mechanics, Twenty-Fourth Symposium, ASTM STP 1207, J. D. Landes, D. E. McCabe and J. A. M Boulet, Eds, ASTM, pp. 442-466.

Milne, I. and Chell, G. G. "Effect of Size on the J Fracture Criterion", Elastic-Plastic, Fracture, ASTM STP 668, J. D. Landes, J. A. Begley and G. A. Clarke, Eds, ASTM, pp. 358-377.

O'Dowd, N. P. & Shih, C.F.(1993), "Two-parameter Fracture Mechanics: Theory and Applications". NUREG/CR-5958. Nuclear Regulatory Commission, Washington, DC.

O'Dowd, N. P. and. Shih, C.F.(1991) "Family of Crack-Tip Fields Characterized by a Triaxiality Parameter: Part I - Structure of Fields', J. Mech. Phys. Solids, vol. 39, pp. 989-1015.

O'Dowd, N. P. and. Shih, C.F. (1992) "Family of Crack-Tip Fields Characterized by a Triaxiality Parameter: Part II - Fracture Applications, J. Mech. Phys. Solids, vol. 40, pp. 939-963.

Paris, P. C. and Sih, G, C.(1965) "Stress Analysis of Cracks", Fracture Toughness Testing and Its Applications, ASTM STP 381, ASTM, Philadelphia, PA, pp. 30-81

Rice, J. R. (1968) "A Path Independent Integral and the Approximate Analysis of Strain Concentrations by Notches and Cracks" Journal of Applied Mechanics, Vol. 35, pp. 379 - 386.

Shih, C. F., O'Dowd, N. P. and Kirk, M. T.(1993) "A Framework for Quantifying Crack Tip Constraint" Constraint Effects in Fracture, ASTM STP 1171, E. M. Hackett, et. al Eds., American Society for Testing and Materials, Philadelphia, pp. 2-20.

Wallin, K.(1993) "Fracture Toughness Transition Curve Shape for Ferritic Structural Steels", Proceedings of the Joint FEFG/ICF International Conference on Fracture of Engineering Materials, Singapore, August 6-8, pp. 83-88

Wells, A. A.(1961) "Unstable Crack Propagation in Metals: Cleavage and Fast Fracture" Proceedings of the Crack Propagation Symposium, Vol. 1, Paper 84, Cranfield, UK.

Xia, L., and Shih, C. F., "Ductile Crack Growth-I. A Numerical Study Using Computational Cells with Microstructurally-Based Length Scales", J. Mech. Phys. Solids, Vol. 43, No. 2, pp. 233-259

Zhou, Z. and Landes, J. D.(1993) "Application of Load Separation and Normalization Methods for Polycarbonate Materials" , International Journal of Fracture, Vol. 63, October, pp. 383-393.

Zhou, Z., Landes, J. D. and Huang, D. (1994), "J-R Curve Calculation with the Normalization Method for Toughened Polymers", Polymer Engineering and Science, Vol. 34, No. 2, January, pp. 128-134

Zhou, Z. (1992) "Development and Application of an Advanced Ductile Fracture Toughness Methodology", Ph.D.. dissertation, The University of Tennessee, Knoxville, TN.

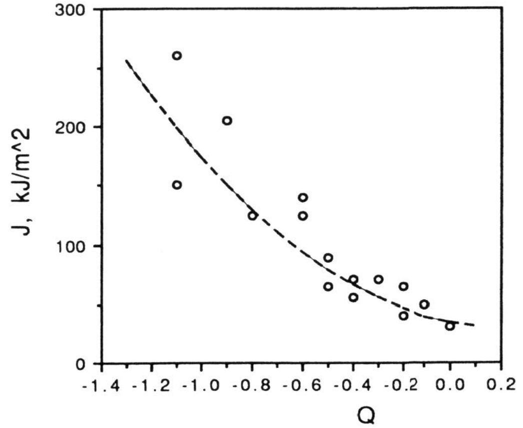

Fig. 1 - J vs Q Fracture Locus

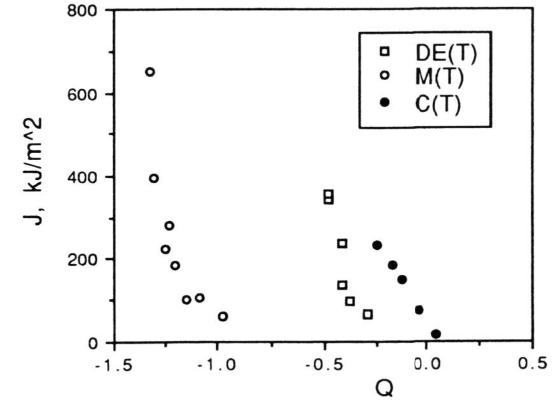

Fig. 2 - J for Transition Fracture vs Q for Different Geometries, C(T), M(T) and DE(T)

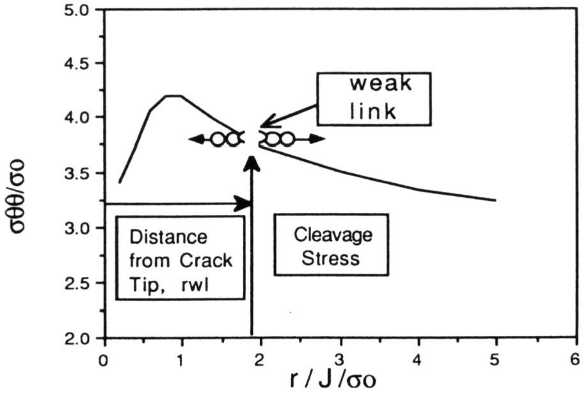

Fig. 3 - J-Q Based Weak Link Model

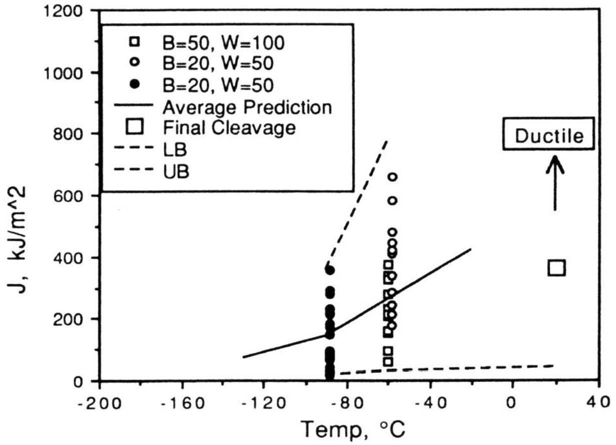

Fig. 4 - Transition Fracture Toughness Prediction for 20MoMnNi55 Steel

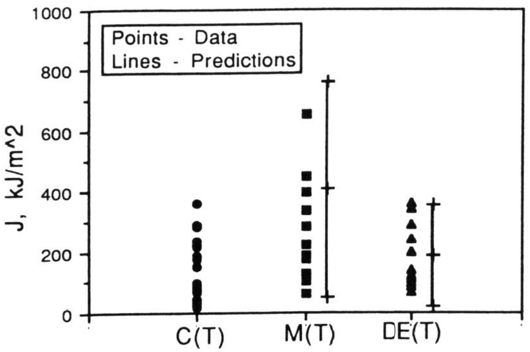

Fig. 5 - Model Predictions for M(T) and DE(T); 20MnMoNi55 Steel at -90 °C

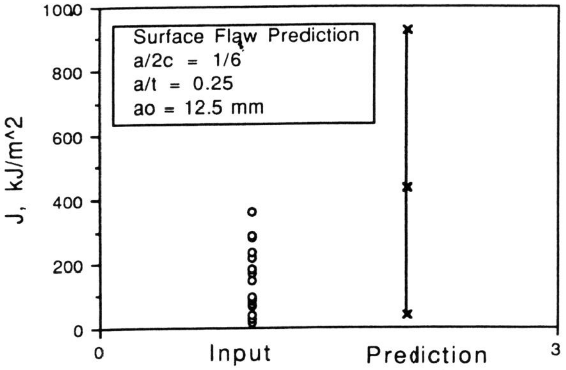

Fig 6 - Model Prediction of Jc for Surface Flaws; 20MnMoNi55 Steel at -90°C

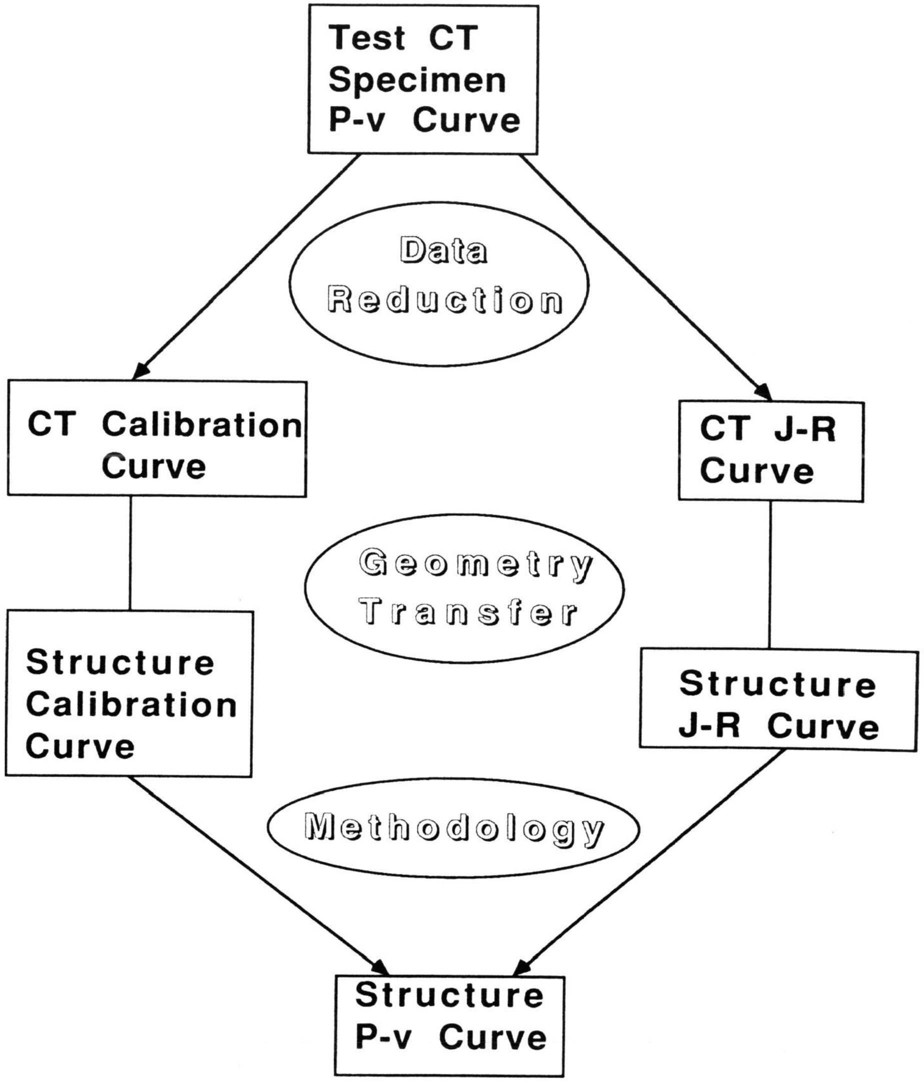

Fig. 7 - Flow Chart of Component Model Load versus Displacement Prediction From Test Specimen

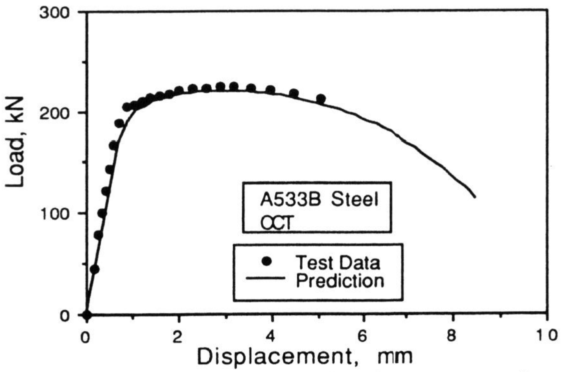

Fig 8 - Load versus Displacement for A533B Steel CCT: Prediction vs Test Data

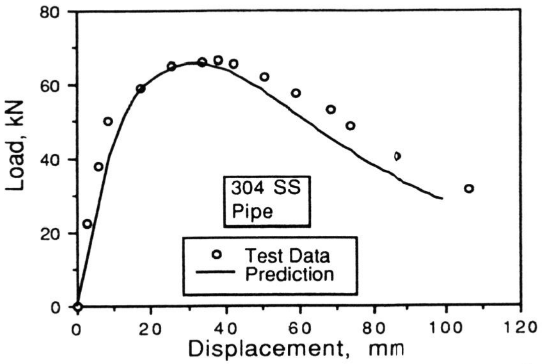

Fig 9 - Load versus Displacement for 304 SS Pipe: Prediction vs Test