A COMMON FORMAT APPROACH FOR APPLYING DUCTILE FRACTURE MECHANICS

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INTRODUCTION

Applications of ductile fracture mechanics methods to the prediction of structural behavior can be done using numerical or analytical methods. Numerical methods can be more accurate but are beyond the capability of some engineering organizations. Also, the result may have relevance only to the specific structure being analyzed. Analytical methods have often used a failure diagram approach in which the failure load of a structure can be estimated. A ductile fracture methodology proposed by Landes et al. [1] takes the load versus displacement for a laboratory specimen and through a series of analytical steps predicts the load versus displacement behavior for a structural component model. The prediction can be made for any geometry where a limit load solution and the fracture parameter calibrations are available. This prediction gives more complete information in that both the maximum load can be determined as well as the stability of the structure after maximum load.

The prediction of the loading behavior during ductile fracture depends on the deformation behavior of the structure and the cracking behavior, usually the former is the more important. The ductile fracture methodology uses a principal of load separation proposed by Ernst [2] in which the loading of a cracked body can be specified by separate but multiplicative functions, one of geometry, that is cracking behavior, and one of deformation. After the load versus displacement for the specimen is separated into these two functional behaviors, a transfer is made for these functions from the specimen geometry to the structural component geometry and the two functions are combined to predict load versus displacement of the structural component model. The procedure is shown schematically in Fig. 1. The entire procedure can theoretically be completed with a hand calculator.

The first proposal of this ductile fracture methodology used a graphical procedure to make the transfer in calibration curves from the specimen to the structural component model. Since that time, additional work has been done on the determination of the deformation behavior for the structural component. Donoso and Landes [3] showed that deformation behavior of any structural component, including test specimens geometries, can be derived from the basic stress-strain behavior of the material. With this, the deformation behavior of the component can be determined from that of the specimen using common functional expressions with similar constants, ones that can

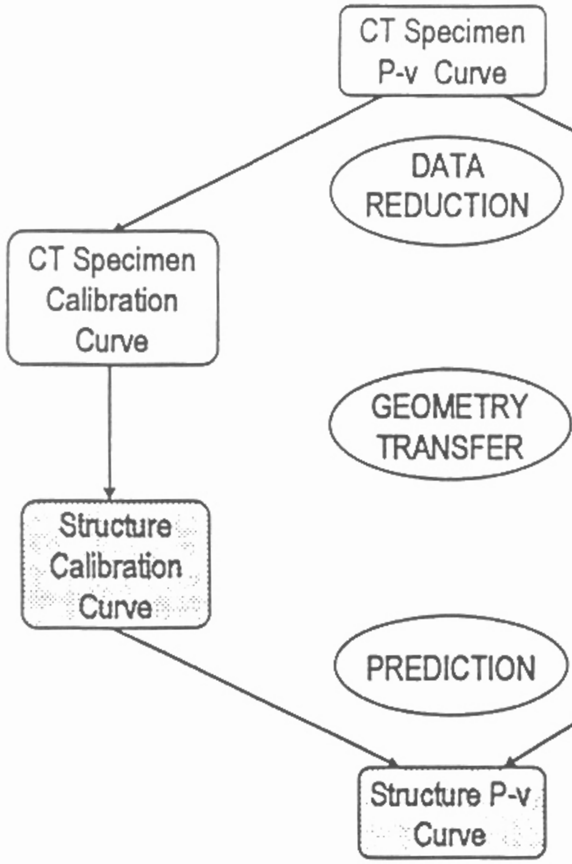

Fig. 1 - Flow Chart of Component Model Load versus Displacement Prediction From Test Specimen

be related to the stress-strain behavior and transferred from one geometry to another with a set of calibration factors that pertain to that geometry. This approach was labeled, the "common format" approach. Using this "common format" approach the ductile fracture methodology can be reformulated so that the graphical transformation procedure can be done analytically.

This paper describes the general ductile fracture methodology using the transformation procedures based on analytical transformation parameters. Also, a suggestion is given to use a direct normalizing technique so that the transformation procedure is automatic. The basic methodology using the transformation functions will be illustrated and examples of its application to several structural component models will be given.

METHODOLOGY

The basic approach to the methodology is given in Fig. 1. The result of a fracture toughness test is a load versus displacement record of the test. This can be separated into a basic deformation curve, P_N versus v_{pl}/W, and a fracture toughness curve J versus Δa. The representation of the load, P, is given by separable functions as

$$P = G(b / W) \cdot H(v_{pl} / W) \tag{1}$$

where the G function depends only on the normalized uncracked ligament length, b/W, and the H function depends on the normalized plastic displacement, v_{pl}/W. Here W is specimen width and provides a dimension for the normalization of the other length variables.

If P is divided by G, a normalized load, P_N, results which is only a function H of plastic displacement.

$$P / G = P_N = H(v_{pl} / W) \tag{2}$$

This represents the deformation character of the material. The deformation function that results from a test can be fitted with a functional form that has some fitting constants. Most often a three parameter *LMN* function is fitted. This is given by

$$P_N = H(v_N) = \frac{(L + M v_N)}{(N + v_N)} v_N \tag{3}$$

where, L, M, and N are fitting constants and v_N is v_{pl}/W.

To predict the behavior of the structural component model, the separated deformation and fracture curves are developed from the test data using a principal called normalization [4]. These are represented as a P_N versus v_{pl}/W curve for deformation (or the H function) behavior of the separated load equation and a J versus Δa R curve for the fracture behavior as shown schematically in Fig. 1. These two represent behavior for the test specimen. To relate them to the structural component model whose behavior is to be predicted a transformation must be done. The transformation is done on this methodology only for the deformation behavior. Transformation for the R curve is under study but cannot be completed until all of the trends are understood [5]. The procedure for the transformation of the deformation curve is shown in Fig. 2. The graphical transformation takes three steps. For the first, the abscissa is renormalized so that v_{pl}/W is replaced by v_{pl}/v_{el}, Fig. 2b. Second, the P_N value is multiplied by an f factor which represents the ratio of the normalized limit loads, Fig. 2c. This gives P_n, the normalized load for the structural model. The factor f is given by

$$f = \frac{P_{Ls} / G_s(a_{os} / W_s)}{P_L / G(a_o / W)} \tag{4}$$

where P_{Ls} and $G_s(a_{os}/W)$ are the limit load and G function of Eq. 1 taken at the initial crack size for the structure a_{os}, and P_L and $G(a_o/W)$ are the limit load and G function at the initial crack size, a_o, for the fracture toughness specimen. Finally for the third step, the abscissa is renormalized back to v_{pl}/W, Fig. 2d. This represents the deformation curve for the structural component.

The common format idea [3] expressed all of the deformation as a transformation from the original stress-strain behavior of the material. Using this concept, the transformation of the deformation property was made by using only an analytical technique. The functional relationships are given by

$$P = (\Omega / \kappa) \cdot G(b / W) \cdot H(v_{pl} / W) \tag{5}$$

where Ω/κ represents the constraint of the geometry, and the G and H function are the same as in Eq. 1.

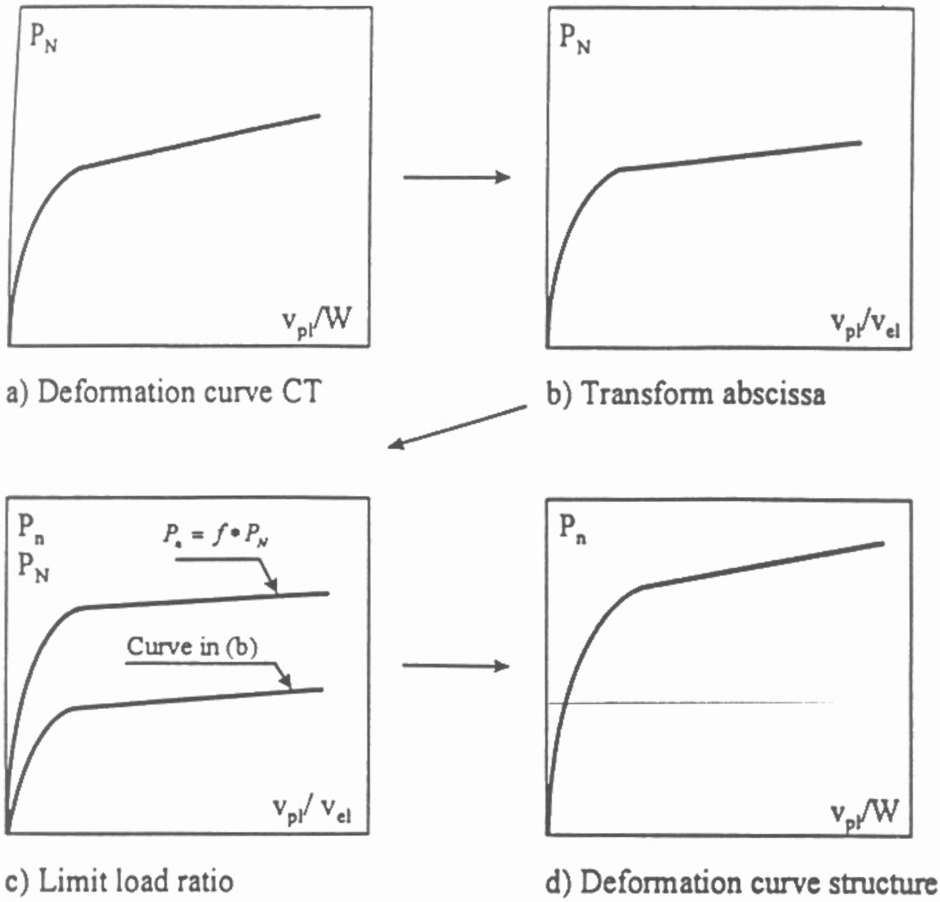

Fig. 2 - Graphical Transformation of the Deformation Curve

The original common format approach was similar to the graphical procedure only in part. The normalized load P_N was transformed using the procedure in the equations. It was found that the abscissa also needed some transformation procedure and this was missing. A modification to the common format approach was suggested which included transformations of both the P_N and the normalized displacement [6]. These are given by

$$P_n = \frac{l + m\nu_n}{n + \nu_n}(\nu_n) = \frac{fL + fqM\nu_N}{(N/q) + \nu_N}(\nu_N) \tag{6}$$

where f is the limit load factor of Eq. 4, ν_n is the normalized displacement for the structural component model and q is given by

$$q = \frac{(\nu_{el}/W)}{(\nu_{el}/W)_s} \tag{7}$$

The transformation of the normalized load is done by a multiplying factor, f, which is the ratio of limit loads. This accounts for the fact that the loading condition between specimen and structural component are different. The transformation of the normalized displacement with q accounts for the fact that the displacement measuring sites are different. It is in some respects a gauge length adjustment. Examples of how the analytical transformation method works are given in the next section.

EXAMPLE APPLICATIONS OF THE METHODOLOGY

The methodology is applied using the graphical and analytical approaches to predict the behavior of three component model geometries from a specimen geometry, the compact geometry, CT. Each of the component geometries has a set of experimental results to compare with the predictions. The geometries are all shown in Fig. 3. They are all tension panels one with a central defect, CCT, one with a single edge defect, SENT, and one with two edge defects, DENT. The material is an A533B steel in a thin section so that the thickness constraint is plane stress for all geometries [7].

The test result for the compact specimen, Fig. 4, is first separated into a deformation curve, Fig. 5a, and a J-R fracture toughness curve, Fig. 5b.The results of the deformation curve for the CT are then transformed into the deformation curves for the CCT, SENT and DENT using both the graphical procedure of Fig. 2 and the analytical procedure of Eq. 6. The results are shown in Figs. 6 a, b and c as the deformation curves P_n versus v_{pl}/W. Both transformations are compared with experimental results in these figures.

Given these transformed deformation curves, the actual load versus displacement curves for the three component models are predicted by combining the deformation curves with the fracture toughness J-R curves. For this prediction two different J-R curves are used, one from the CT test result and one from the test of the component geometry. The results are shown in Figs. 7 a, b and c where they are compared with the experimental result.

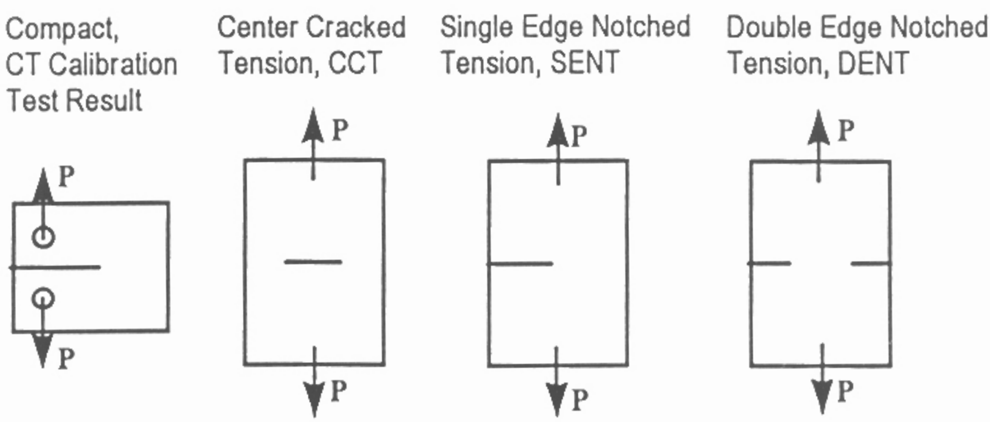

Fig 3 - Schematic of Component Geometries Used in Calibration Curve Transfer

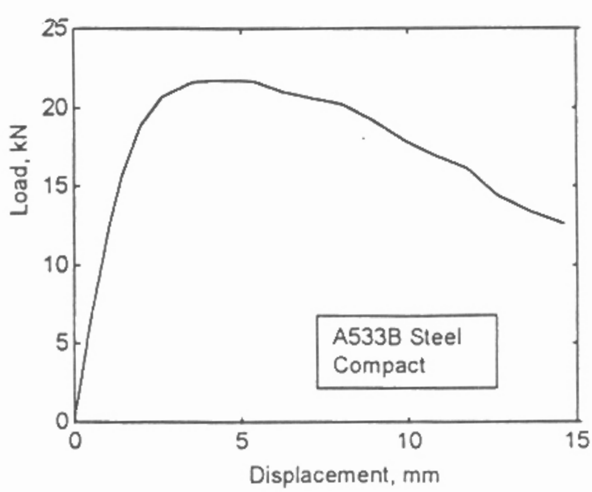

Fig. 4 - Load versus Displacement for A533B Steel Compact Specimen

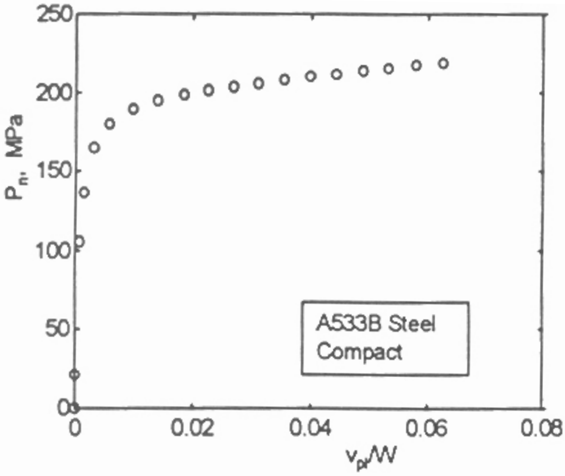

Fig. 5a - Normalized Load versus Plastic Displacement for A533B Compact

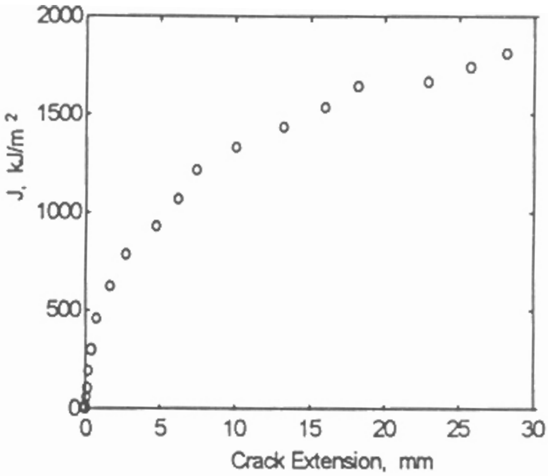

Fig. 5b - J-R Curve for A533B Steel Compact

DISCUSSION

The results given in Figs. 6 and 7 show a fairly good agreement with the experimental result. Both of the transformation procedures used predict the deformation curve well. They are actually two ways to do the same transformation. However, the prediction of the actual load versus displacement curve for the component models is best done with the actual R curve from that test. In a blind prediction, this component R curve would not be known and the prediction could be made using only the R curve from the CT specimen test. This does predict the maximum load fairly well, but does not predict the load and displacement well after the maximum load is attained.

The reason for the difficulty in prediction of the curve after maximum load is that the J-R curves for the different geometries show a big geometry dependence. This effect is discussed in Ref. 5 which shows that the R curve are raised as the planar constraint is decreased. Correspondingly, the R curve is raised from that of the CT to the SENT. Then it is raised more from the SENT to the DENT and finally the most for the CCT. The results in Fig. 7 shows the best prediction from the CT R curve for the SENT and the worst for the CCT. To make a better prediction of the actual load versus displacement records, the J-R curve from the CT test would also have to be transformed. This is not presently done because all of the geometry effects are not understood. Numerical work is being done to look at the effect of planar constraint on the J-R curve [8].

The procedure using the CT R curve predicts the maximum load fairly accurately. Only the load versus displacement after maximum load is not predicted as well. Other assessment methods do not try to predict displacement values and are concerned only with the prediction of the maximum load. These may often give more variation in the prediction of the maximum load than the methodology presented here does.

The transformation procedure requires a renormalization of the abscissa in the deformation curve from v_{pl}/W to v_{pl}/v_{el} and back. The graphical procedure takes several steps to do this and the analytical procedure of Eq. 6 takes a separate calculation. To streamline the transformation procedure, the suggestion has been made that the initial normalization of the deformation curve could be made by v_{pl}/v_{el} in Eq. 1 and with this the transformation of the abscissa could be eliminated. This has been discussed in [9].

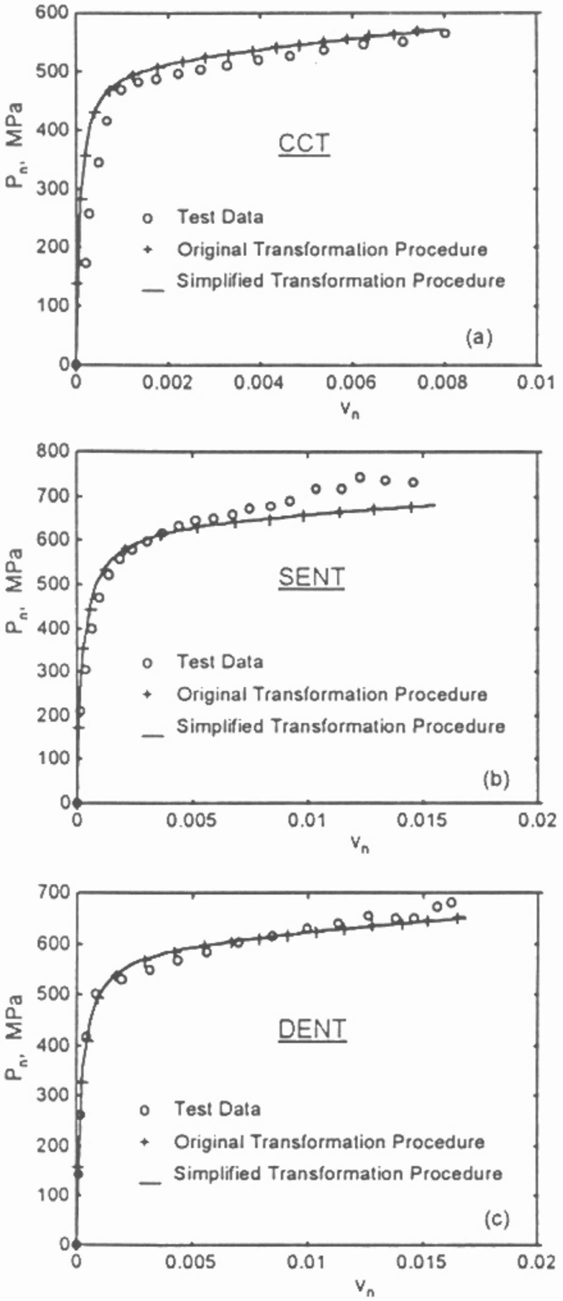

Fig. 6 - Prediction of Deformation Curves

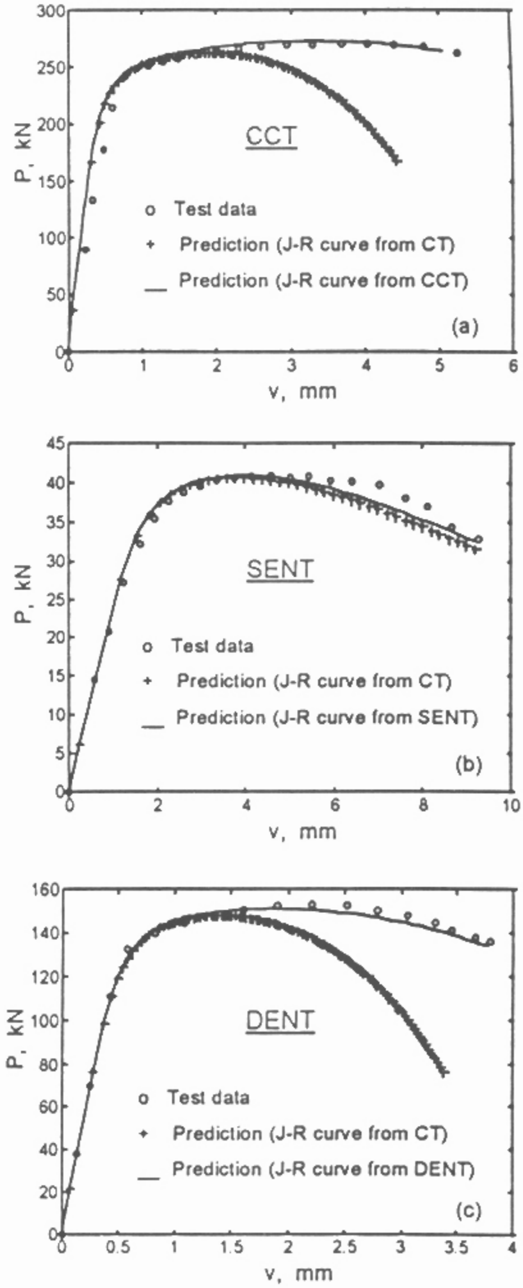

Fig. 7 - Prediction of the Load vs Displacement Curves

SUMMARY

A methodology for prediction of the load versus displacement behavior for a structural component model containing a crack-like defect is presented. This methodology is based on a principal of load separation and a deformation transformation procedure that assumes that the deformation of a model component relates directly to the stress-strain behavior of the material. The method divides the test result into a deformation curve and a J-R curve. These two behaviors can be related to the structural component of interest through a transformation process that predicts the separated deformation and fracture behaviors for the structural geometry of interest. The deformation and fracture are then recombined to give a prediction in the form of load versus displacement behavior of the structural component. Examples of the predication procedure are given for structural component models where the behavior is predicted from the fracture toughness test result of a compact specimen.

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