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# *Evaluation of the Crack Plane Equilibrium Model for Predicting Plastic Fracture*

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# Evaluation of the Crack Plane Equilibrium Model for Predicting Plastic Fracture

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EVALUATION OF THE CRACK PLANE EQUILIBRIUM
MODEL FOR PREDICTING PLASTIC FRACTURE

by

T. A. Butler and F. W. Smith

ABSTRACT

A simple model for predicting the initiation of crack growth during plastic fracture is evaluated. The model is based on requiring equilibrium between applied loads and an assumed stress distribution in the uncracked ligament near the crack. The fracture parameters required are the material's ultimate tensile strength and a process-zone size at the crack tip that is determined from simple fracture tests. The Crack Plane Equilibrium model predicts crack-growth initiation for the crack geometries studied with sufficient accuracy to warrant extending it for investigating other geometries and for predicting stable crack growth and the onset of unstable crack growth.

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## I. INTRODUCTION

A major safety benefit of Liquid Metal Fast Breeder Reactors (LMFBRs) over Light Water Reactors (LWRs) is that a breach in the primary piping system in the LMFBR is much more likely to be detected before it can develop into a major coolant leak that might lead to a serious accident challenging the reactor containment. This capability to detect a small leak before a pipe breaks (leak-before-break) exists because of the relatively low system pressure, the pipe geometry, and the ductile material properties of the stainless steel pipe. Under normal service conditions, flaws that exist in the piping will grow through the pipe wall before they lengthen enough to cause either stable or unstable crack growth under increasing loads. However, under faulted conditions or during beyond-design-base accidents, the system can be loaded with excessive pressures, external loads, and temperature, rendering it less obvious that the piping will experience leak-before-break.

The question to be addressed is whether flaws that exist in the piping could grow to critical sizes and geometries before leaks are detected. In answering this question, we must examine flaw growth under fatigue and creep conditions, initiation of crack growth under increasing loads, crack-growth characteristics under excessive loads including creep effects, and, finally, conditions leading to the onset of unstable crack growth. Ductile fracture in the stainless steel that constitutes the primary pressure boundary for loop-type LMFBRs is characterized by extensive blunting at a flaw and large amounts of plasticity before crack growth begins. In this report we direct our attention to the determination of the load- and crack-size combinations that lead to the initiation of crack growth under increasing load. A proposed method for extending the technique to predict stable crack growth and the onset of crack instability is briefly described.

Over the past several years, a large amount of work has been performed to develop methods for predicting crack-growth characteristics in LWR piping, most of this work centering around J-analysis techniques described by Paris et al.[1] Recent work has been performed by Kanninen et al.[2] and Kumar, German, and Shih[3] to develop detailed engineering methodologies, based on the work of Paris and others, for predicting elastic-plastic fracture. Kanninen et al.[2] evaluate several possible plastic fracture approaches and determine that a combination of the J-integral and Crack Tip Opening Angle (CTOA) used with a resistance curve approach is the most useful and accurate technique. The J-resistance curve is used to predict the crack-growth initiation and a small amount of stable growth; a computed CTOA value is then used to predict larger amounts of stable crack growth up to failure. Kumar, German, and Shih[3] take a similar approach using either analytical or finite-element calculations of the J-integral and Crack Opening Displacement (COD) in conjunction with experimentally determined J- and COD-resistance curves. They proceed to predict initiation of crack growth, stable crack growth, and conditions leading to instability.

Another technique used for prediction of crack-growth initiation and subsequent fracture is the net-section stress. This is a very simple technique where crack-growth initiation and fracture are dictated by an assumed uniform stress reaching critical values over the uncracked ligament. These values are called the critical flow stresses and lie between the yield and ultimate stress for the material being evaluated. Two different critical-stress values are required: one predicting the initiation of crack growth and the other predicting fracture. The critical values of flow stress are determined through tests with simple Center Cracked Tensile (CCT) specimens; these values can then be applied to more complex pipe geometries. Kanninen et al.[4] apply this technique to cracked pipe sections. Shih et al.[5] also suggest that the technique is appropriate for stainless steel piping if an "appropriately adjusted flow stress is employed."

In this report we evaluate a method similar to the net-section stress approach for predicting the initiation of crack growth. The method is based on the Crack Plane Equilibrium (CPE) model and uses a more realistic assumed stress distribution than the constant stress assumed for the net-section stress approach. The CPE model also uses a measured fracture parameter termed the process-zone size and is, therefore, not as geometry-dependent as the net-section stress criterion.

Following sections describe the model, apply it to two common crack geometries, and suggest extensions for predicting stable crack growth, including the effects of creep, and for predicting fracture. Results are also compared with the J-analysis and net-section stress techniques.

## II. DESCRIPTION OF THE CPE MODEL

The CPE model is based on the concept of requiring equilibrium between the force applied to a cracked structural section and the distribution of stress that must exist in the plane of the crack. The approach assumes a distribution of stress in the plane of the crack that is similar to the stress distribution found in the J-integral formulation of Hutchinson[6] and Rice and Rosengren.[7] The form of the assumed stress state in the CPE model is such that for ductile materials the stress distribution found in Refs. 6 and 7 is recovered. In addition, for situations where linear elastic conditions exist, the stress distribution assumed corresponds to the elastic solution for a simple crack in a wide plate.

In this approach the singularities that exist in the assumed stress distribution are eliminated by requiring the existence of a process zone over which the stress achieves the level of the ultimate stress of the material involved, as determined from a uniaxial tension test. By requiring the assumed distribution of stress to be in equilibrium with the applied stress on the component at failure, we can estimate the stress at which failure of the crack tip commences (crack-growth initiation). The fracture parameters in this model are the size of the process zone and the ultimate strength of the material.

The technique has some advantages in that it has been shown to have reasonable accuracy for the CCT specimen and certain surface flaw geometries,[8,9] and produces equations that can be easily solved for the prediction of the initiation of crack propagation. Simple CCT specimen fracture tests can be conducted in material with a thickness appropriate for the problem of interest to determine the process-zone size parameter in the model. It has been shown in Ref. 8 that, for similar conditions of temperature and environment, the process-zone size parameter can be transferred to a different crack geometry, and the model will predict failure within 10% accuracy. Further, under linear elastic conditions the model predicts the same results as would be predicted by linear elastic fracture mechanics theory. The disadvantages of the model are that it is approximate in nature, predicts only the initiation of crack propagation, and in its current form, does not deal with stable slow growth or creep-crack growth.

In the following paragraphs the predictive equations will be derived for the CCT specimen shown in Fig. 1. Equations presented later for geometries other than the CCT specimen can be derived by using similar techniques and accounting for differences in geometry. The essential feature of the CPE model is the assumed distribution of stress ahead of the crack shown in Fig. 1. The form that is assumed for this distribution is

$$\sigma(x) = \sigma_{ult} = \text{constant} \qquad a \leq x \leq a + \Delta \tag{1a}$$

$$\sigma(x) = A \left[ \frac{x^2}{x^2 - a^2} \right]^{n/(n+1)} \qquad a + \Delta \leq x \leq W/2 \quad , \tag{1b}$$

where

$$A = \sigma_{ult} \Bigg/ \left[ \frac{(a + \Delta)^2}{(a + \Delta)^2 - a^2} \right]^{n/(n+1)} .$$

In these equations $\Delta$ is the size of the process zone (Fig. 1). The stress distribution used in Eq. (1b) reduces to that found by Hutchinson and Rice and Rosengren in Refs. 6 and 7 for the case where x is only slightly larger than a. Next, equilibrium between the applied stress and the assumed stress distribution in the cracked plane is required, resulting in

$$\sigma_i = \sigma_{ult} \ \frac{2\ \Delta}{W} + \frac{2A}{W} \left[ \int_{a+\ \Delta}^{w/2} \frac{X^2}{X^2 - a^2} \right]^{n/n+1} dx \ . \tag{2}$$

It is possible to numerically evaluate the integral in Eq. (2) and to calculate the remaining terms once the quantity $\Delta$ is determined from simple fracture tests. Having done this, it is possible to calculate the engineering stress at the condition of failure, $\sigma_i$, defined by the onset of crack

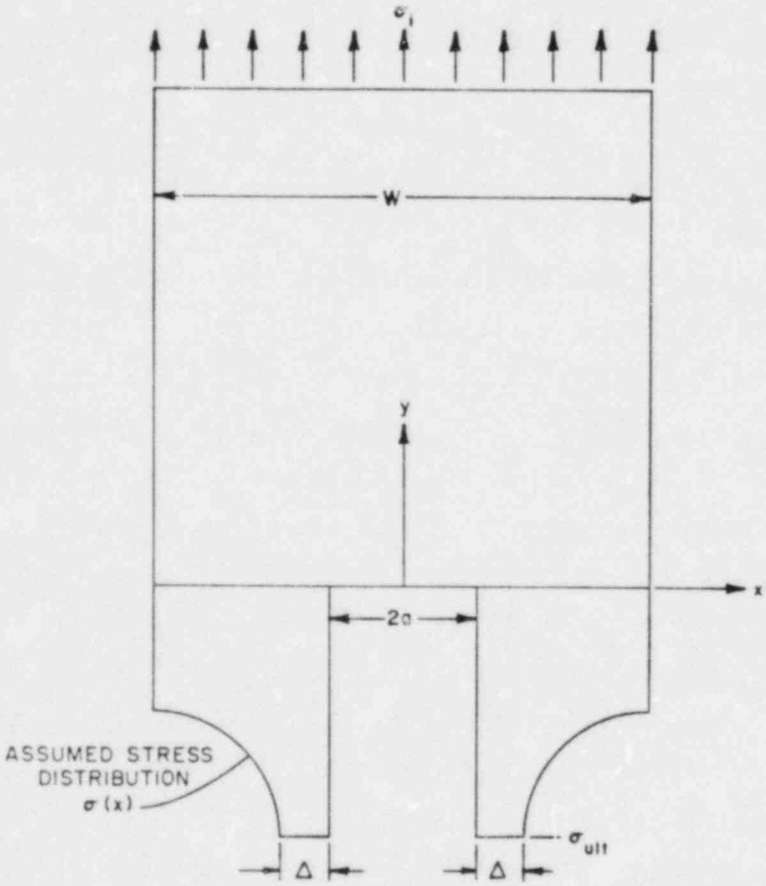


Fig. 1. Equilibrium condition for CCT specimen.

propagation. This approach makes use of the post-yield engineering stress-strain curve for the determination of n, the strain-hardening coefficient for $\sigma_{ult}$, the ultimate strain. The analysis is greatly simplified by making use of the original dimensions of the component rather than attempting to account for the large changes in geometry that occur because of the extreme ductility of materials such as 304 or 316 stainless steel. Experience indicates that this assumption yields reasonable accuracy. Smith and Nelson,[9] making use of the CPE approach for the CCT specimen, included the effects of large deformations mentioned above and found that some improvement in accuracy resulted. However, as will be shown in later sections, the level of approximation included here is adequate in cases considered so far.

Similar derivations can be made for several other crack geometries of practical interest in LMFBR design problems. In addition to the CCT specimen, equations have been derived for a part-through, full-circumferential crack in a pipe. Other crack geometries that could be treated include an axial crack through the wall of a pipe, a circumferential through-crack extending only part way around the circumference of a pipe, the compact tensile specimen, and the single-edge cracked plate.

## III. APPLICATION OF THE CPE MODEL

As described in the previous section, the fracture parameters for the CPE model are the ultimate tensile strength, $\sigma_{ult}$, and the fracture process-zone size, $\Delta$. The strain hardening coefficient for the material being considered is also required. The ultimate tensile strength and the strain-hardening coefficient are determined from either uniaxial tensile tests or available handbook data. Based on the engineering stress-strain curve beyond the material yield point, the strain-hardening coefficient can be determined by assuming that this portion of the curve plots as a straight line on log-log paper and then obtaining a best-fit curve.

Size of the process zone for 304 SS at room temperature was determined from a set of CCT specimen data given in Ref. 9; based on uniaxial data from that same reference, the ultimate tensile strength and strain-hardening coefficient were determined. These data, along with similar data for 304 SS at 205°C (400°F) and 546°C (1015°F), are shown in Table I. Also shown in Table I are other room-temperature data needed for comparison with results reported in the noted references. The CPE model for the CCT specimen was then used to select a process-zone size 2.5 mm (0.10 in.) that causes the predicted curve to pass through a selected data point. The resulting CPE prediction along with the test data are presented in Fig. 2. Note that, even though the model was forced to fit only one point by varying $\Delta$, the prediction provides a close fit for all the test data. In this figure and those that follow, the failure stress, $\sigma_i$, is normalized by the flow stress, $\sigma$, where $\sigma \equiv 1/2\ (\sigma_{ult} + \sigma_y)$ and $\sigma_{ult}$ and $\sigma_y$ vary with the specific material being considered. The dashed line in the figure represents the failure stresses that would be predicted using the net-section stress criterion with the flow stress defined as above.

When the total crack length in the CCT specimen exceeds approximately half the plate width, the CPE prediction has the same slope as the net-section stress criterion line; it is, however, approximately 22% higher. This difference in magnitude means that if the net-section stress criterion was used for this case with $\sigma = 1/2\ (\sigma_{ult} + \sigma_y)$, conservative failure predictions would result. We can adjust the flow stress to be $0.625\ (\sigma_{ult} + \sigma_y)$ and obtain a close fit for the net-section stress criterion. A comparison of this adjusted flow stress to the CPE model stress distribution is shown in Fig. 3. The adjusted flow stress is essentially an average of the CPE model stress distribution.

With the appropriate fracture parameters determined, we checked to see whether the model can predict other experimental data. Kanninen et al.[4] present a limited amount of CCT specimen data that we have used for this

TABLE I

MATERIAL PROPERTIES FOR 304 SS

| Temperature °C (°F) | Ultimate Tensile Strength MPa (psi) | Yield Strength MPa (psi) | Strain-Hardening Coefficient |
|---|---|---|---|
| 25 (77) Ref. 9 | 648 (94000) | 302 (43800) | 0.200 |
| 25 (77) Ref. 4 | 630 (91370) | 265 (38430) | 0.200 |
| 25 (77) Ref. 10 | 572 (83000) | 207 (30000) | 0.200 |
| 205 (400) Ref. 4 | 460 (66710) | 180 (26100) | 0.225 |
| 546 (1015) | 402 (58280) | 117 (17000) | 0.250 |

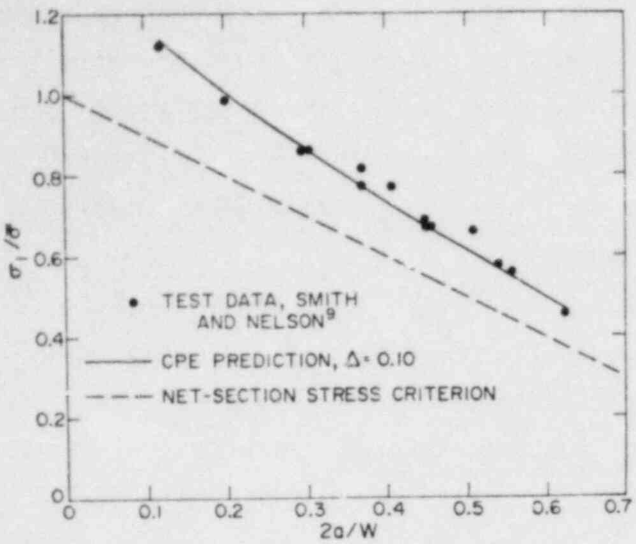


Fig. 2. CPE prediction compared with test data for 2.5-in. wide CCT specimen of 304 SS at room temperature.

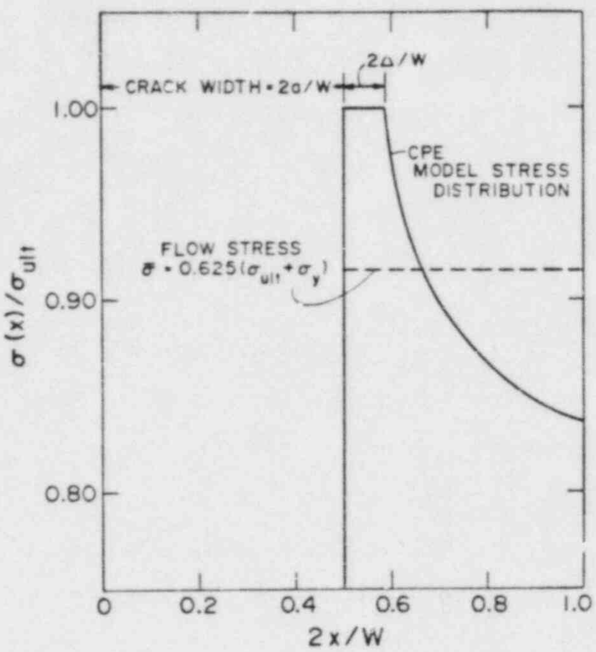


Fig. 3. Stress distributions in remaining ligament of CCT specimen.

purpose. Their CCT specimen was 0.305 m (12 in.) wide and 7.94 mm (0.3125 in.) thick; Fig. 4 shows the correlation of the CPE model with these data. A process-zone width, Δ, of 2.5 mm (0.10 in.) was used with $\sigma_{ult}$ equal to 630 MPa (91370 psi). The model overpredicts the stress at crack-growth initiation by as much as 21%. If we use the net-section stress criterion with the flow stress adjusted as suggested above [for example, $\sigma = 0.625\ (\sigma_{ult} + \sigma_y)$], the failure stress is overpredicted by 42%.

Considering the data from the two test series (Refs. 4 and 9), it is not surprising that both the CPE model and the net-section stress criterion overpredict stress at crack-growth initiation for the larger CCT specimens (those used in Ref. 9). Note from the data presented in Fig. 5 that the small CCT specimen used by Smith and Nelson[9] has a significantly higher (up to 43%) crack-growth initiation stress than the larger specimen used by Kanninen et al.[4] for the same crack length-to-width ratio. Part of this difference may be attributed to two geometric effects: first, different amounts of constraint caused by different material thicknesses (should be negligible because the larger test specimens are only 25% thicker than the small specimens); second,

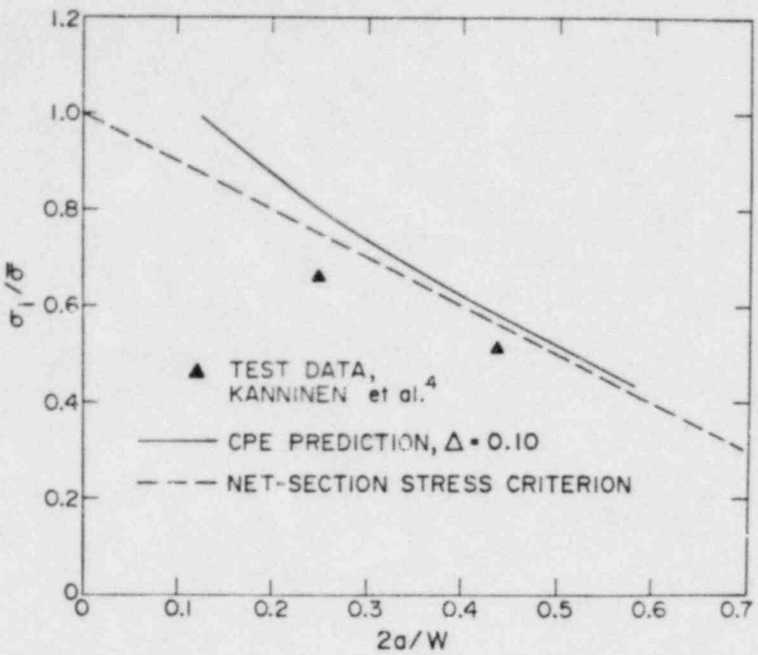


Fig. 4. CPE prediction compared with test data for 12-in.-wide CCT specimen of 304 SS at room temperature.

a geometric effect arising from differences in the ratio of specimen width to process-zone size. The limit of this latter effect would be in a very narrow specimen when the uncracked ligament is equal to or less than the process-zone width. Such a specimen would theoretically fail when the applied stress was equal to the ultimate stress. Based on the CPE model, this effect accounts for 18.5% of the difference between the two independent data sets for 2a/W = 0.4 and 17% of the difference for 2a/W = 0.25.

Other potential causes for differences in the two data sets include material-properties differences and differences in experimental apparatus and techniques. Material-properties differences are negligible and, as can be seen from the data in Table I, will account for differences of only a few per cent. Smith and Nelson[9] used a standard MTS clamp that distributed the load evenly across the CCT specimen; Kanninen et al.[4] used a centrally located pin. Because of the large length-to-width ratio of the specimens, the differences in loading method should have had a negligible effect. In both sets of experiments, the onset of crack growth was noted visually. Smith and Nelson[9] report that no stable crack growth occurred, so the force-deflection curve was very flat when crack growth was initiated. However, Kanninen et al.[4] report considerable stable crack growth. This difference in the occurrence of stable

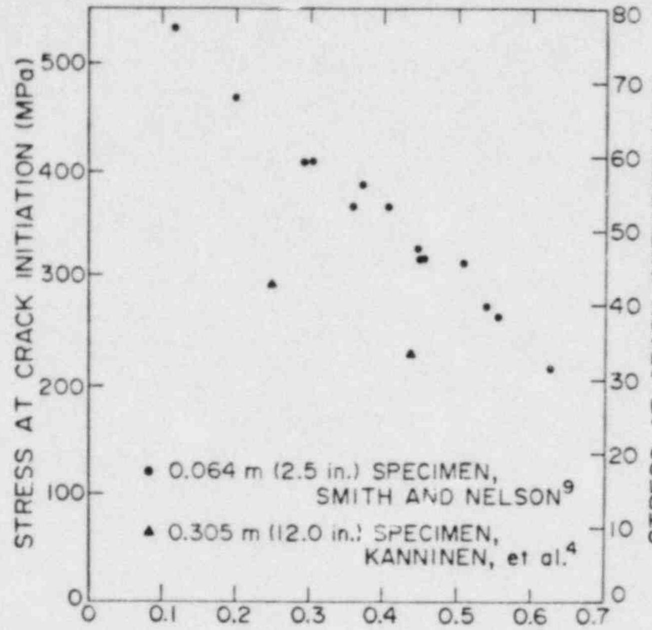


Fig. 5. Crack-growth initiation data for CCT specimens.

crack growth is possibly the most significant finding in comparing the two data sets. We do not currently have an explanation for the phenomenon and recommend a test series to investigate it more thoroughly. For completeness, we show the stress where unstable crack growth occurred for the larger specimens in Figs. 4 and 5; note from Fig. 4 that these fall very near the CPE-model prediction.

Figure 6 shows CPE-model predictions for a CCT specimen at 205°C (400°F) along with two data points from Ref. 4. We do not currently have process-zone size information for 304 SS at this temperature, so two process-zone sizes were used for the calculations. The first process-zone size was chosen equal to that determined earlier for 304 SS at room temperature. The second was chosen equal to half the first, showing that this range envelops the test data. The two resulting failure curves are virtually parallel and, for large cracks, they both parallel the net-section stress criterion with $\sigma = 1/2\ (\sigma_{ult} + \sigma_y)$.

To check the CPE model for more realistic piping flaws, we considered the case of a full-circumferential, part-through crack with the pipe under axial tensile load (Fig. 7). The particular pipe studied had an outside radius of 0.102 m (4 in.) and a wall thickness of 10.2 mm (0.4 in.). Material properties

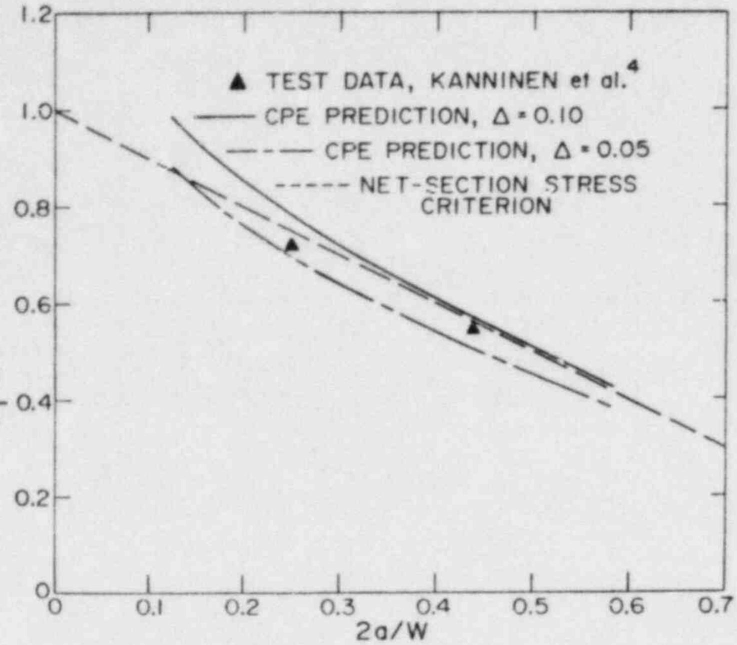


Fig. 6. CPE prediction compared with test data for 12-in.-wide CCT specimen of 304 SS at 205°C.

were at room temperature, so we used a process-zone width of 0.10 in. Appropriate test data for comparison could not be located, so we have used data points from a J-analysis performed with analytical J-integral solutions.[10] Results (Fig. 7) indicate that the CPE model is a viable candidate for making failure predictions for this configuration in that the CPE-model prediction is close to the J-analysis predictions (maximum difference in results is 14%); nevertheless, both should be verified with appropriate tests for the crack configuration. Note that for the net-section stress criterion to apply for this configuration, a flow stress, $\sigma$, of 0.75 ($\sigma_{ult}$ + $\sigma_y$) would have to be used.

E. Smith[11] found that, for this crack configuration, the net-section stress at the onset of radial crack extension is dependent on crack depth and values of the critical net-section flow stress can vary by as much as a factor of 2 for a given material. On the other hand, the CPE model uses a fracture parameter, the process-zone width, that helps reduce geometry dependence. As mentioned earlier in this report, the CPE model process-zone size may have some geometry dependence in that it will vary to some degree with specimen thickness because of constraint effects. Further testing is required to determine the extent of the constraint effect and other geometrical factors. Initial tests would be performed with CCT specimens, and test parameters

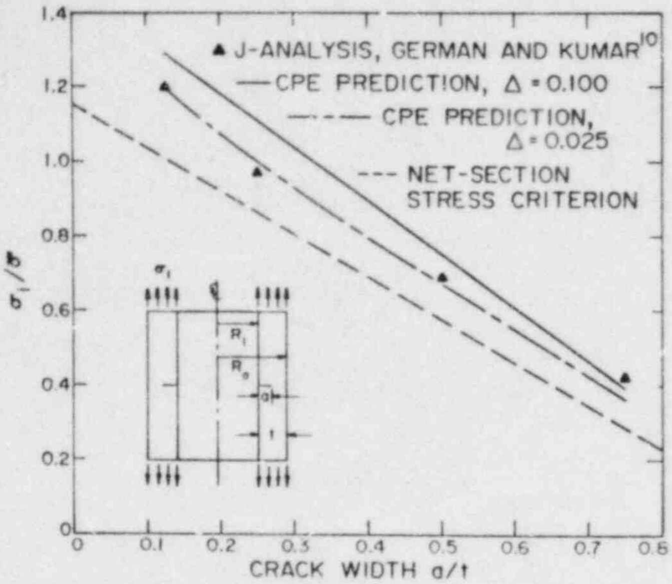


Fig. 7. CPE prediction compared with J analysis for full-circumferential, part-through crack in pipe under axial load at room temperature.

should include specimens with several different width-to-thickness ratios. Some of the tests should be performed at LMFBR operating temperatures.

To determine the sensitivity of the CPE model to key parameters, we performed a sensitivity study using the cracked-pipe configuration described above. However, we used geometry and material properties consistent with a typical LMFBR pipe at 546$^{o}$C (1015$^{o}$F), including an outside radius of 0.305 m (12 in.) and a wall thickness of 0.127 mm (0.5 in.). Material properties are given in Table I. First, all parameters were held constant and the process-zone size was varied; results of this study are presented in Fig. 8. Second, the strain-hardening coefficient, n, was varied and the process-zone size was set at a constant value of 0.10 in.; these results are shown in Fig. 9. This sensitivity study shows that, for this particular crack geometry, the CPE model is insensitive to a wide range of strain-hardening coefficients (a similar study with the CCT specimen showed more sensitivity to the strain-hardening coefficient). Predictions are more sensitive to the process-zone size but do not vary widely. Investigation of the CPE equations shows that the predicted failure stress is directly proportional to the other fracture parameter, $\sigma_{ult}$. Based on these observations, for a given material, $\sigma_{ult}$ must be very accurately measured, the process-zone size, Δ, may be determined with less accuracy (as few as two or three CCT specimens may be required for each material and temperature), and the strain-hardening coefficient need only be approximated for this geometry.

## IV. EXTENDING THE CPE MODEL

In its current state of development, although the CPE approach allows prediction of the onset of crack propagation, it cannot distinguish between stable

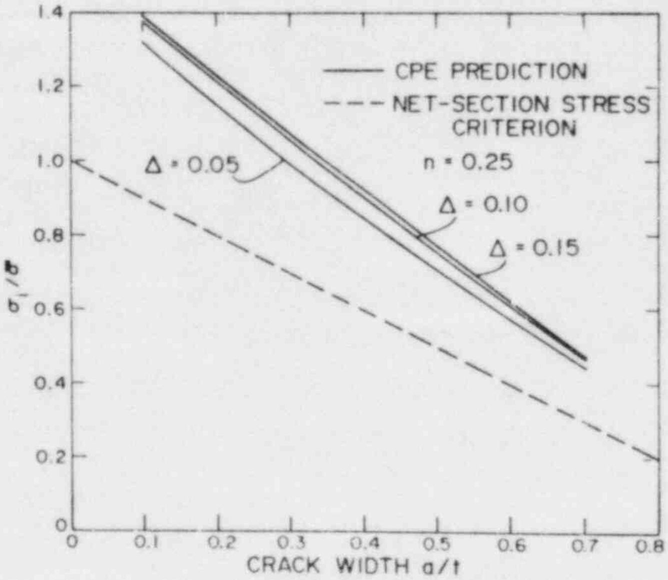


Fig. 8. CPE prediction for full-circumferential, part-through crack in pipe under axial load at 546°C (1015°F).

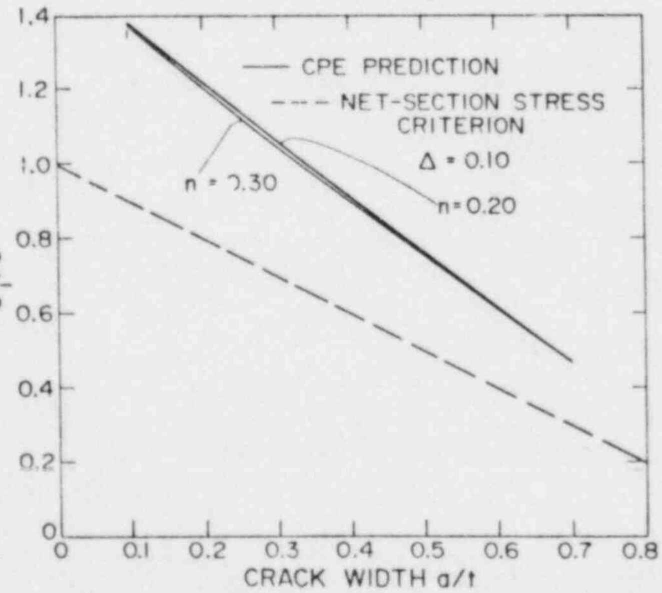


Fig. 9. CPE prediction for full-circumferential, part-through crack in pipe under axial load at 546°C (1015°F).

and unstable growth, and it does not deal with creep-crack propagation. We anticipate performing simple laboratory fracture tests to determine the process-zone size parameter in the predictive models. It will also be necessary to conduct uniaxial tension tests or use existing data for appropriate temperature conditions to determine the ultimate strength and strain-hardening coefficients for the model. We will also start development of predictive models for crack geometries and loading situations that have not yet been considered. By introducing more sophisticated assumptions regarding the failure at the crack tip, it should be possible to introduce the capability for predicting creep-crack growth behavior. This added capability will require development of a creep-rupture model representing the material in the process zone immediately ahead of the crack tip. Finally, an approach is being developed to couple the CPE model with a finite-element analysis of any crack problem; such an analysis would have to account for large deformation and nonlinear material behavior. Figure 10 shows how this approach would work. An idealized finite-element mesh is shown near the region of the crack tip. In the analysis, vertical constraints are placed along the symmetry plane as shown in the figure. At appropriate stages of the finite-element analysis, the nodal point forces are determined at the position of the constraints. For the region immediately ahead of the crack tip, these forces must be in equilibrium with a locally assumed stress distribution in much the same way as was done in the derivation for the CCT specimen. For the conditions of onset of crack propagation, it

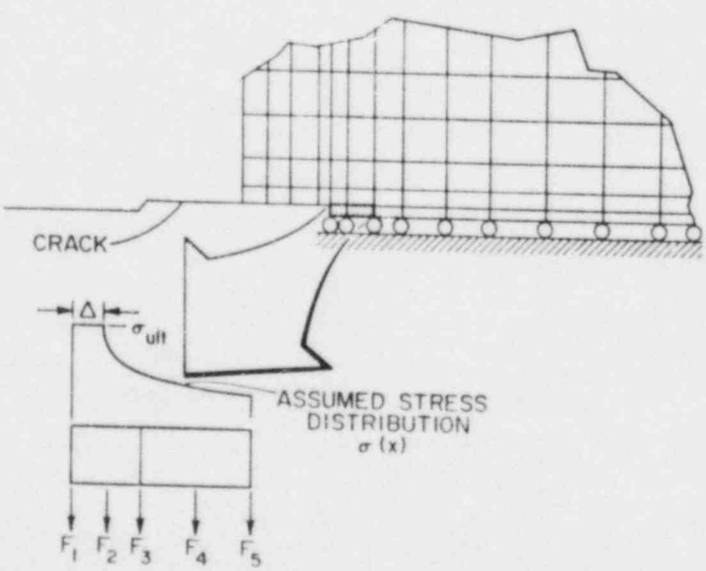


Fig. 10. Equilibrium on finite elements near a crack tip.

will be possible to calculate the level of stress operating in the process zone. We have already seen that, when the stress in the process zone reaches the critical level, propagation begins. Earlier work[9] indicates that this approach should be successful, at least for predicting the onset of propagation. Moreover, it will have the additional advantage that the finite-element model would be representing nonlinear material behavior and large deformation behavior, and, thus, these effects would be included in the prediction. Further, if a finite-element code is used that allows elastic unloading in its plasticity formulation, it should be possible to assess the stability of crack growth.

## V. CONCLUSIONS AND RECOMMENDATIONS

A model for predicting the initiation of crack growth has been evaluated for some basic crack geometries. This evaluation has led to the following conclusions:

1. The major advantage of the CPE model is its portability from one crack geometry to another. Additional geometries must be studied and data obtained to verify the analytical model for these geometries.
2. One required fracture parameter, the process-zone size, can be obtained from a small number of fracture tests at the appropriate temperature using the CCT specimen. The other fracture parameter, the material's ultimate tensile strength, is obtained from normal uniaxial tests.
3. Further tests with CCT specimens with varying width-to-thickness ratios are recommended for determining geometry dependence of the process-zone size. CCT specimen tests at 546°C (1015°F) should be performed to obtain the process-zone size for typical LMFBR temperatures.
4. The CPE model predicts the initiation of crack growth in CCT specimens and full-circumferential, part-through cracked pipes under axial loads accurately enough to warrant further study with other crack geometries at higher temperatures.
5. A method is proposed for extending the CPE model for predicting stable crack growth and crack instability using elastic-plastic finite-element analyses. We recommend that this procedure be evaluated for a

simple crack geometry (for example, CCT specimen) to determine its worth.

6. We recommend that the CPE model be used to investigate progressively more complex crack geometries. This may require a hybrid approach using elastic-plastic finite-element models.

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14 ABSTRACT (200 words or less)

A simple model for predicting the initiation of crack growth during plastic fracture is evaluated. The model is based on requiring equilibrium between applied loads and an assumed stress distribution in the uncracked ligament near the crack. The fracture parameters required are the material's ultimate tensile strength and a process-zone size at the crack tip that is determined from simple fracture tests. The Crack Plane Equilibrium model predicts crack-growth initiation for the crack geometries studied with sufficient accuracy to warrant extending it for investigating other geometries and for predicting stable crack growth and the onset of unstable crack growth.

15a KEY WORDS AND DOCUMENT ANALYSIS

15b DESCRIPTORS

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