APPLICATION OF A DUCTILE FRACTURE METHODOLOGY TO A PRESSURE VESSEL NOZZLE CRACK

Julio R. B. Cruz
IPEN-CNEN/SP, São Paulo, SP, Brasil

John D. Landes
University of Tennessee, Knoxville, TN, USA

ABSTRACT

A ductile fracture methodology is applied to a high-pressure polyethylene reactor vessel containing a nozzle corner crack. Results are determined in terms of critical pressure for failure as a function of the initial crack length. A comparison is made with a safe analysis done with PD6493 followed by a discussion about the two approaches.

1. INTRODUCTION

A ductile fracture methodology (DFM) (Landes et al., 1993) has been developed which can take the load versus displacement record from a laboratory test specimen containing a crack-like defect and predict the same for a structural component containing a defect. The methodology has been applied to systems that have loading parameters that can be described by a remotely applied load and a load point displacement. For systems that do not have the loading described by these parameters, the methodology lacks formulation parameters to make this prediction. A pressure vessel is a structural geometry that does not have these well-defined loading parameters because the loading is usually given as an internally applied pressure with no displacement equivalent. Nevertheless, the methodology can be used if a deformation pattern for the cracked vessel geometry is available.

In this paper, the DFM is applied to predict the structural behavior of a high-pressure polyethylene reactor vessel. The junctions of radial holes and the vessel wall are the most critical regions of a polyethylene reactor. Thus, a nozzle corner crack is postulated and the methodology is employed to predict the failure conditions for the pressure vessel nozzle problem. The results are then compared with a safe analysis performed with the procedures of PD6493 (1991).

2. METHODOLOGY

The basic approach to the methodology is shown schematically in Fig. 1. The result of a fracture toughness test is a load versus displacement record of the test. Applying a procedure called normalization (Landes et al., 1991), the load versus displacement record can be separated into a calibration function (which represents the deformation behavior) and a fracture toughness curve J versus Δa (which represents the cracking behavior). These two represent behavior for the test specimen. To relate them to the structural component whose behavior is to be predicted a geometry transfer step must be accomplished to obtain the same information for the structural component. Then, the separation process is reversed and a load versus displacement curve for the structure is predicted.

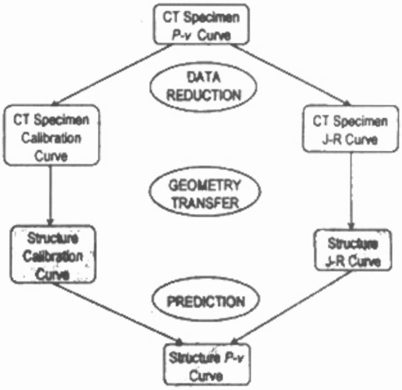

Figure 1. Flow chart of structure load versus displacement prediction from test specimen

The DFM is founded on the load separation concept proposed by Ernst (1981). According to this concept, the relationship between load, P, crack length, a, and plastic displacement, v_{pl}, for a cracked body can be expressed as a multiplication of two separable functions

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

where $G(a/W)$ is a function of geometry only and $H(v_{pl}/W)$ is a function of plastic deformation only. W is a length dimension normalization parameter; for test specimen geometries, W is usually the width, but for a structural component, it could be another dimension, such as the thickness. When the load P is divided by the $G(a/W)$ function, the result is a normalized load, P_N, which is a function only of v_{pl}/W

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

The information in Eq. 2 is often referred to as the calibration function. It can describe the deformation behavior of the cracked body for a certain value of crack length. The G function is known for several geometries or can be obtained in a relatively easy way (Sharobeam and Landes, 1991). Thus, the H function can be obtained for the test specimen from the load versus displacement test record using Eq. 2. The transformation of the calibration curve (the H function) from the specimen geometry to the structural component geometry can be done using the original procedure proposed by Landes et al. (1993) or a simplified approach suggested by Cruz and Landes (1999).

If the analytical expressions for G and H are known for the geometry of the structure, the crack driving force given in terms of the J integral can be readily calculated for the current values of crack length, a, and plastic displacement, v_{pl}, using the following expression

$$J = J_{el} + J_{pl} = \frac{K^2}{E'} + \frac{\eta_{pl}}{Bb}\int_0^{v_{pl}} P dv_{pl} \qquad (3)$$

where K is the linear elastic stress-intensity factor, E' is the effective modulus of elasticity, η_{pl} is the plastic η-factor, B is the structural thickness, and b is an uncracked ligament length. The total displacement, v, is also calculated as a sum of an elastic and a plastic component

$$v = v_{el} + v_{pl} \qquad (4)$$

and the relationship between v_{el} and P is given in terms of the compliance, C, that is

$$v_{el} = C(a/W) \cdot P \qquad (5)$$

Equations 1 to 5 along with a J-R fracture toughness curve can describe the complete load versus displacement behavior of a structure containing a crack-like defect. The load versus displacement is predicted by the calibration function, Eq. 2. This equation represents a family of curves for different stationary cracks. The appropriate curve to follow during the loading process depends upon the current crack length, which is obtained from the J-R curve for the current value of J applied, which is also calculated during the loading process. This process continues with the calibration function giving the relationship between the load and displacement for a given value of crack length and the J-R curve indicating what current value of crack length should be used. When small increments in crack length are used, the loading follows a smooth path. That is the basic idea of the DFM.

In the way it was described above, the methodology has been applied to systems in which the loading process can be represented by a remotely applied load versus load point displacement. That is not the case of a pressure vessel where the loading is usually given as an internally applied pressure with no displacement equivalent. Thus, for the pressure vessel analyzed herein, the complete methodology is not applied. Rather only the bottom part of the scheme shown in Fig. 1 is used. Figure 2 illustrates the predicting procedure that will be applied for the vessel assessment. The deformation pattern is given in terms of pressure versus J calibration curves, each curve for a different stationary crack length. This information is then combined with the J-R curve of material. For a given initial crack length, a_o, and considering a certain amount of crack growth, results a pressure versus J curve, from which the critical pressure can then be predicted.

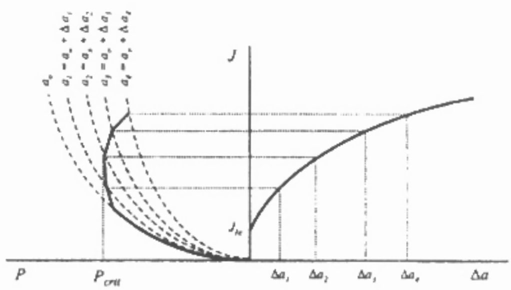

Figure 2. Scheme for predicting the critical pressure

3. PROBLEM DATA

Loading. The reactor operating pressure is 200 MPa and the operating temperature is 200 °C.

Geometry. Part of an axial section of the vessel is shown in Fig. 3. The main dimensions of the vessel are: total length = 7.543 m; inner diameter = 0.413 m; and outer diameter = 0.699 m. The nozzle being analyzed is the one on the right side, which has a diameter of 3" (0.076 m).

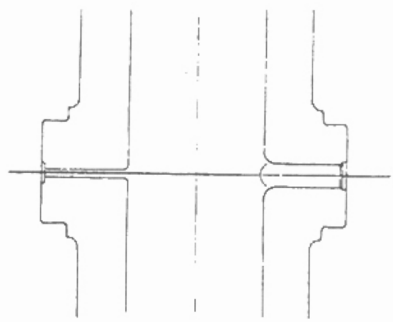

Figure 3. Part of an axial section of the vessel

Material Properties. Yield strength (σ_y) = 827.4 MPa; ultimate tensile strength (σ_u) = 930.8 MPa; Young's modulus (E) = 173793 MPa; fracture toughness is given in terms of a J-R curve, which is shown in Fig. 4.

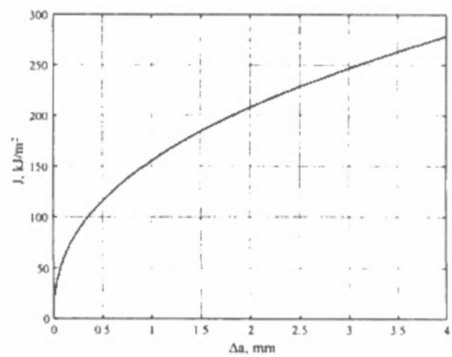

Figure 4. Material J-R curve

4. ANALYSIS

The analysis with the DFM determines the critical pressure for failure as a function of the initial crack length. The first step for applying the predicting procedure illustrated in Fig. 2 is to get the pressure versus J calibration curves for the cracked vessel nozzle geometry. The J applied to the structure can be determined as a sum of an elastic component and a plastic component.

Elastic Component of *J*. The elastic component of J is obtained from the linear elastic stress intensity factor using the following equation

$$J_{el} = \frac{K_I^2}{E} \tag{6}$$

The K_I (Mode I stress intensity factor) solution, taken from a Handbook (Zahoor, 1989), is for an axial part-circular flaw located at the nozzle corner (Fig. 5). The value of K_I is at the deepest point on the flaw and is given by

$$K_I = p(\pi a)^{0.5} \cdot (A_0 G_0 + A_1 G_1) \tag{7}$$

where p is the internal pressure, a is the flaw depth, and A_i are the coefficients of the stress polynomial describing the hoop stress (σ_h) variation through the nozzle wall at the postulated flaw location and are defined as

$$\sigma_h = p[A_o + A_1(z/t')] \tag{8}$$

where z is the distance measured from the inner surface of the nozzle corner and t' is a reference wall thickness at the nozzle corner. G_i, in Eq. 7, are the influence coefficients associated with the coefficients of the stress polynomial A_i and may be expressed by the following general form:

$$G_i = A + B(a/R_n) + C(a/R_n)^2 + D(a/R_n)^3 + E(a/R_n)^4 + F(a/R_n)^5 \tag{9}$$

where R_n is the apparent radius of the nozzle (see Fig. 5). The numerical values of the coefficients A through F are tabulated in the Handbook for each G_i. The applicability of this solution is for $0.02 \leq a/R_n \leq 0.4$.

Plastic Component of *J*. The plastic component of J is computed using the following expression

$$J_{pl} = \frac{\alpha\mu K_I^2}{E}\left(\frac{P}{P_o}\right)^{n-1} \tag{10}$$

The is a simplified solution proposed by Ainsworth (1984) that allows one to obtain J_{pl} from K_I; α and n are coefficients of the Ramberg-Osgood equation which is assumed for the material stress-strain behavior; $\mu = 0.75$ for plane strain and $\mu = 1$ for plane stress; and P_o is the limit load.

Since α and n were not available for the material, they were estimated using a procedure proposed by Bloom (1982) that resulted in $\alpha = 1.3$ and $n = 13$. The expression used for the limit load was taken from a nozzle corner flaw 2-D model presented in the Handbook (Zahoor, 1989). A flow stress, taken as the average between σ_y and σ_u, was used to compute P_o.

Failure Assessment. The coefficients A_0 and A_1 of Eq. 7 were calculated from the linearized hoop stress variation through the nozzle wall obtained from finite element results. With all data available and computing the total J as a sum of J_{el} and J_{pl}, an expression relating internal pressure and J applied was taken. This expression was then used to obtain the pressure versus J calibration curves, so that the predicting procedure depicted in Fig. 2 could be applied.

The first prediction was done for an initial crack depth of 20 mm. The result is presented in Fig 6, which shows the pressure versus J calibration curves (dashed lines) and the curve that results from combining this information with the J-R curve of the material. The first dashed line on the left corresponds to the initial crack depth and the others are for crack growth increments of 0.5 mm (a proportional crack front growth was assumed). The critical pressure obtained for this case was 374 MPa.

A second prediction was made considering the initial crack depth equal to 10.5 mm. That is the critical crack depth obtained in a safe analysis made for this vessel with PD6493 in which the vessel internal pressure was taken as 250 MPa. The result obtained with the DFM is shown in Fig. 7. The critical pressure found was 560 MPa.

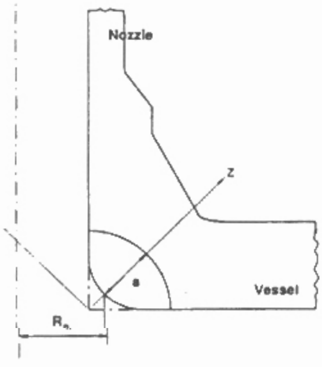

Figure 5. Axial part-circular nozzle corner flaw

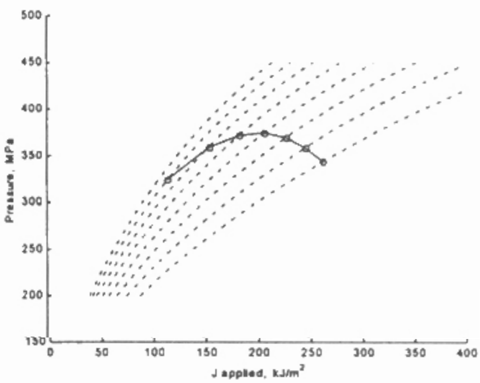

Figure 6. Prediction of the critical pressure for a_o = 20 mm

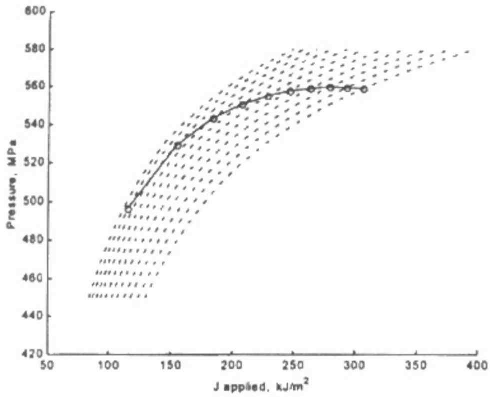

Figure 7. Prediction of the critical pressure for a_o = 10.5 mm

5. COMPARISON WITH PD6493 RESULTS

The same vessel problem was analyzed in another paper presented at this conference ("Estudo de Integridade Estrutural em Reator Tipo Auto-Clave, de Alta Pressão, para Produção de Polietileno de Baixa Densidade") using the procedures of PD6493 (1991). The evaluation was done for levels 1 and 2 of PD6493. The comparison with the DFM results will be made here only for the assessment done with level 2 of PD6493, since level 1 is too conservative and is intended more as a screening tool.

The analysis with PD6493 was done for an internal pressure of 250 MPa and the critical crack depth found was 10.5 mm. As shown before, for the same crack depth, the pressure determined with the DFM that would cause failure of the vessel is 560 MPa. A further analysis was done with the DFM in order to find to which critical crack depth would correspond the pressure of 250 MPa. It was found a value of 22.83 mm. This crack depth exceeds slightly the applicability limit of the K_I solution used, but is acceptable for a comparison. As can be seen, the result obtained with PD6493 is much more conservative. Follow some considerations in an attempt to explain the difference between the results obtained with the two approaches.

The K_I solution chosen to make the prediction with the DFM is based on a cracked geometry, which represents accurately the actual structure, that is a nozzle corner flaw. On the other hand, level 2 of PD6493 is based on the plane stress strip yield model approach. It uses a failure assessment diagram (FAD) to determine safe areas of loading for the cracked structure. The FAD curve represents a transition between brittle fracture governed by linear elastic fracture mechanics (LEFM) and plastic collapse governed by the limit load. Although the same failure curve is used for the assessment of different geometries subjected to different stress states, the equation of this curve was derived from the expression of the effective stress intensity factor for a through crack in an infinite plate under plane stress. Therefore, the assessment done with PD6493 has some embedded conservatism to account for uncertainties in variability of toughness, stress levels and other data.

Besides, the DFM is a more modern approach, which incorporates elastic-plastic fracture mechanics (EPFM) concepts. If the cracked component supports some stable crack growth, the method allow it to occur in the predicting process, which combines, step by step, as the load increases monotonically, the deformation behavior (given by the calibration curves) and fracture behavior (given by the J-R curve). Thus, a more precise prediction of the critical conditions for failure is expected.

6. CONCLUSIONS

The DFM methodology was applied to predict the failure condition of a polyethylene reactor vessel containing a nozzle corner crack. The results obtained with the DFM were compared with a safe analysis done with PD6493. This is a more conservative method than the DFM and seeks to develop safe limits. It is formulated in a way that the method can be used following a well-prescribed set of rules. Level 2 of PD6493 does not incorporate any EPFM concepts. Plasticity effects are taken into account by means of an approximate transition curve that goes from brittle fracture to plastic collapse behavior. On the other hand, the DFM is based on EPFM concepts and attempts to predict the actual failure condition of the structural component. Since it is a more realistic method and does not include any safety factor, this could explain the factor of approximately 2 between the critical crack depth predicted by the DFM and the one predicted by PD6493.

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