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Welded Joint Integrity Analysis: Relative Criticality of Weld Defect and Remote Deformation

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Mechanics of Materials Branch
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Structural integrity problems which deal with welded sections are common in the pressure vessel and piping industry. The current work uses continuum fracture toughness concepts to determine the structural integrity of a butt welded plate with a lack of penetration defect in the weld material. The difference in weld and base metal properties are explicitly included in the computational simulation. The analysis technique presented does not require the analyst to assume a failure location. The critical strain energy density associated with fracture of a material at the continuum scale is used as the failure criterion.

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CONTENTS

WELDED JOINT INTEGRITY ANALYSIS: RELATIVE CRITICALITY OF WELD DEFECT AND REMOTE DEFORMATION

INTRODUCTION

Welded joints are an essential part of pressure vessel and piping systems as well as the support structures for these systems. Defects due to lack of penetration and inclusion of slag can exist as artifacts of the welding process. The sensitivity of welded structures to defects is of concern to the designer and structural analyst.

The presence of defects in a weld can be determined by non-destructive test techniques such as ultrasonic and radiographic examination. If the presence of a defect has been established it is essential to determine whether the defect is detrimental to the structure. Arbitrary limits on defect dimensions tend to be based on workmanship quality rather than detailed analytical evaluation of weld strength [1]. In contrast to workmanship quality defined allowable defect dimensions, investigations attempting to quantify the process of determining an acceptable defect size have been completed [2,3]. It is important to not remove defects which do not limit the performance capability of a structure because of the weld performance degradation which may occur as a result of the repair process [1].

Information which is essential to the analytical structural integrity evaluation of a welded joint include (1) the defect size, position and orientation, (2) the structure and weld geometry, (3) applied loading information, (4) material response of both weld metal and base metal and (5) weldment fabrication information. The structural integrity evaluation of a welded joint is a process complicated by component geometry and inhomogeneous material composition which result in nonuniform deformation fields. Even when high levels of material and manufacturing quality are combined with the simplest of geometries, welded structure integrity assurance must address issues such as the gradient of material properties across the weld metal, heat affected zone and base metal.

One analysis method often used for the structural integrity evaluation of welded joint with a known defect is an analytical evaluation of the most severe type of defect possible. The resulting evaluation is a fracture mechanics analysis of a crack-like defect. Linear elastic fracture theories have been used to successfully predict brittle fracture. However, brittle fracture is only one of the possible failure mechanisms associated with the presence of a defect in a weldment [4]. High toughness materials may exhibit large

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amounts of local deformation prior to fracture. In order to accurately predict failure in high toughness materials, damage and fracture theories which address ductile behavior are required.

Many failure criteria have been proposed for ductile materials. Predominant among the failure criteria proposed are contour integrals such as J [5] and crack tip opening displacement [6]. Some early work in the determination of ductile failure criteria used correction factors to extend the region of applicability of linear elastic fracture mechanics by representing the effects of plasticity around the crack tip [7,8]. However, only a limited amount of plasticity can be accounted for by correction factors.

In general, when there is a relatively small amount of plasticity around the crack tip, failure criteria based on linear elastic concepts can be used successfully. However, in instances where large amounts of plasticity occur prior to failure, analysis methods based on linear elastic concepts are no longer capable of approximating the state of stress and strain near the crack tip. In order to accurately represent the state of stress and strain near the crack tip the analysis method and failure criteria used should explicitly include large deformation constitutive response.

The explicit consideration of ductile material behavior prior to fracture does not in and of itself alleviate all limitations which may be associated with a particular fracture mechanics analysis technique. Present day fracture mechanics analysis techniques have limitations which must be taken into consideration [9]. Limitations common to fracture mechanics analysis techniques include the mathematical prediction of physically unattainable conditions such as the existence of a stress, strain and strain energy density singularity, correct material characterization and the appropriateness of the chosen fracture criterion. The material characterization used for ductile fracture should include an accurate description of large strain response. The failure criterion for ductile fracture should not be limited by the amount of local deformation which occurs prior to fracture. Other areas of concern which may exist for specific problems include availability of suitable data to adequately characterize material deformation, effects of loading rate and history, interpretations of material data scatter and defect characterization.

In addition to the various limitations listed above, a feature common to many fracture criteria is the assumption that failure occurs at a dominant crack or defect which is observed or assumed to exist in the structure. Since failure is assumed to occur at a crack or a defect, these features must be present in the test specimen used to determine the critical values of the parameters in the fracture criterion.

A material damage and failure criterion which explicitly addresses ductile behavior can be developed based on a general continuum approach which utilizes the constitutive relations to describe deformation, damage and fracture by the continuous point variables of stress, strain and energy density. Continuum material toughness [10] is one such material damage and fracture criterion and is used in the current analysis. For a structural analysis, the geometry and boundary conditions which define the problem and the constitutive relations representing the material are used in a computational solution for the stress, strain and energy density fields. The critical locations in the structure are identified from the computational simulation and the load or time to failure is determined from the local stress, strain and energy density histories. A priori assumptions regarding the location and mode of failure are not required. The failure criterion used is the strain energy density required to produce material fracture at the continuum scale. The use of an energy density as a failure criterion is consistent with the concepts presented by Freudenthal [11] on material behavior and scaling considerations. Previous work by Gillemot [12] used analytical and empirical techniques to determine the strain energy density per unit volume at fracture for cylindrical tensile specimens. The strain energy per unit volume absorbed by the material up to the instant of fracture was calculated from global specimen load-displacement response and deformed geometry. A computational simulation of a welded T-section using the strain energy density at the continuum scale as the failure criterion was performed by Matic and Jolles [13]. The critical strain energy density was determined from continuum stress-strain information obtained from tensile tests and percent reduction in area in a manner similar to that detailed in the current work. The failure load obtained from a nonlinear finite element analysis compared favorably with the failure load obtained from a laboratory test of the T-section performed subsequent to the numerical prediction.

In the current work strain energy density concepts and analysis procedures are reviewed and applied in a structural integrity analysis of a butt welded plate with a lack of penetration defect in the weld. The fracture initiation load and location of failures are determined from a finite element simulation. The butt welded plate is chosen because it is a geometric simple joint which is frequently encountered.

CONTINUUM MATERIAL TOUGHNESS CONCEPTS

A continuum volume of material undergoing deformation is characterized by its multiaxial stress and strain state, σ_{ij} and ε_{ij}, respectively. For ductile metals, and other materials which exhibit inelastic deformation, the strain state is a function of the stress history as well as the stress state. The state of stress and strain may be related by a constitutive formulation which defines the strain increment $\Delta\varepsilon_{ij}$ from the current stress state.

The strain energy per unit mass at a given instant during deformation is:

$$w = \lim_{\Delta V \to 0} \frac{\rho \Delta W}{\Delta V} \tag{1}$$

$$= \int_0^{\varepsilon_{ij}} \frac{\sigma_{ij} d\varepsilon_{ij}}{\rho} \tag{2}$$

where ρ is the mass density. The energy density incorporates both stress and strain into a fundamental quantity relevant to thermodynamic description of material deformation and damage. The energy density is a scalar quantity which takes into account all components of the stress and strain tensors in a physically consistent manner. Failure of the material, at the continuum scale, can be associated with the value of the energy density at which fracture occurs. Thus, the material toughness may be defined as:

$$w_c = \int_0^{(\varepsilon_{ij})_c} \frac{\sigma_{ij} d\varepsilon_{ij}}{\rho} \tag{3}$$

where w_c is the critical strain energy density. The value of w_c can be considered as a material property for structural analyses.

For ductile materials, the material density varies only slightly, even over large deformations. For this reason, it is possible to define an energy per unit volume density as:

$$w = \lim_{\Delta V \to 0} \frac{\Delta W}{\Delta V} \tag{4}$$

$$= \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij} \tag{5}$$

with an associated critical value

$$w_c = \int_0^{(\varepsilon_{ij})_c} \sigma_{ij} d\varepsilon_{ij} \tag{6}$$

The energy per unit mass is fundamental, however the energy per unit volume is equally appropriate for constant volume deformation processes.

For the case of an uniaxial stress-strain curve, corresponding to a one-dimensional state of deformation, the critical strain energy density corresponds to the area under the uniaxial stress-strain curve:

$$w_c = \int_0^{\varepsilon_c} \sigma d\varepsilon \tag{7}$$

This representation is desirable for use with traditional constitutive formulations which rely on equivalent uniaxial stress-strain curves. In the general case of multiaxial stress and strain, the strain energy density is the sum of the integrals of the individual stress and strain components.

A structural integrity analysis should identify the location of fracture imitation as well as the value of the failure load. A priori selection of the fracture initiation site should not be necessary. In multi-material structures, a relative strain energy density ratio may be used to determine the location of failure and to establish the relative tendency for fracture in each constituent material. The relative strain energy density is the ratio of the local strain energy density attained in the loading process divided by the appropriate local critical strain energy density:

$$\left[\frac{w}{w_c}\right]_n < 1.0 \qquad n=1, 2, 3, \ldots, N \tag{8}$$

where N is the total number of materials in the structure. When values of this ratio are less than unity, fracture initiation does not occur. When the relative strain energy density ratio reaches unity at a site in one of the constituent material, represented by n_c, so that

$$\left[\frac{w}{w_c}\right]_{n_c} = 1.0 \tag{9}$$

and

$$\left[\frac{w}{w_c}\right]_n < 1.0 \qquad n=1, \ldots, n_c-1, n_c+1, \ldots, N \tag{10}$$

fracture occurs in material n_c.

BUTT WELDED PLATE ANLAYSIS

Butt Welded Plate Geometry

The structural integrity of a butt welded plate with a lack of penetration defect (Figure 1) is evaluated using strain energy density as the failure criterion. The butt welded plate evaluated is typical of the type of welded joint which may be found in a pressure vessel or piping support system. The plate evaluated would be part of a larger structure. The length of the defect embedded in the weldment is one-third of the plate thickness. This is sufficient to be identified by non-destructive examination techniques [14]. The base metal is HT structural steel and the weld was made using short arc welding.

The butt welded plate is 0.1875 inch (.4762 cm) thick, 192 inches (488 cm) long and 24 inches (61 cm) wide. A uniform tensile load is applied to the plate in the longitudinal direction.

The weldline is located at the center of the plate in the longitudinal direction and spans the entire width of the plate. A lack of penetration defect is included in the model at the weld centerline. The defect geometry and dimensions are shown in Figure 1. The defect is assumed to be considerably longer in the plate width direction that in the plate thickness direction.

Material Characterization

Data from flat welded tensile specimens was available to characterize base metal and weld metal material behavior. The specimens were 0.2 inches (0.5 cm) thick base metal plates which had been welded together. The welded plates were cut into flat tensile specimens with the weldline spanning the specimen width.

The specimens fractured in either the base metal adjacent to the weld metal or in the weld metal itself. No explicit treatment of the heat affected zone was made due to the tensile specimen size and geometry. The occurrences of fracture in the base metal adjacent to the weld included the effects of the heat affected zone, in an average sense, in the base metal characterization. Standard Cauchy stress-logarithmic strain curves were developed from specimen load displacement data. The stress-strain curves exhibited significant scatter but no distinguishing trend differentiating base metal failure and weld metal failure specimens (Figure 2). The percent reduction in area (%RA), however, while also exhibiting scatter, clearly divided the failed specimens into two distinct groups. The base metal failures fell into the range of 33.0 - 67.0 %RA while the weld metal failures fell into the range of 0.5 - 6.3 %RA.

The marked difference between base metal and weld metal ductility is not apparent from uniaxial considerations alone. Accurate evaluations of the different material toughnesses requires accurate equivalent Cauchy stress-logarithmic strain representations. Such representations should quantitatively reflect the material ductility present in three-dimensional states of deformation. In order to accomplish this quantitative representation continuum stress-strain curves for the base metal and the weld metal (Figure 3) were generated using a procedure previously applied to ductile materials [15]. The procedure is based on results which indicate that the actual continuum stress-strain curves will be more nonlinear than either the standard Cauchy stress-logarithmic strain curve determined from data spanning the entire range of deformation or stress-strain curves extrapolated from small strain data. Subsequent to the work presented in this paper refinements of the procedure have been reported [16,17].

The critical strain energy density of the base metal at fracture was calculated based on the average base metal %RA. Average base metal %RA was used since the base metal was essentially defect free and the %RA is influenced by weld geometry, which may be either detrimental or beneficial to the apparent base metal toughness. The base metal critical strain energy density determined from the continuum stress-strain curves and the average %RA is 54,023 psi. (372.5 MPa).

The critical strain energy density of the weld metal was calculated based on the maximum weld metal %RA. The maximum %RA was used since the presence of lack of penetration defects in the weld metal will tend to degrade the strength of the weld metal resulting in an reduction in the apparent toughness in a manner similar to the reduction in weldment fatigue strength caused by the presence of defects [18]. The maximum %RA is the limiting case which minimizes the influence of defects in the weld metal failure specimen and provides a lower bound on the weld metal material toughness. The critical strain energy density for the weld metal determined from the continuum stress-strain curves and the maximum %RA is 4087 psi. (28.2 MPa).

Computational Modeling

The ABAQUS finite element code [19] was used for the computational evaluation of the butt welded plate. Defect and plate geometry allow for two-dimensional plane strain modeling of the center section of the plate. The finite element model (Figure 4) includes weld metal and base metal regions.

A total of 51 type CPE8 and CPE8H continuum elements were used to model the butt welded plate. The mesh is more refined in the vicinity of the defect because of the local variation in strain energy density expected in this region. The elements used are 8-noded continuum plane strain elements with quadratic displacement interpolation. In addition to displacement interpolation the CPE8H elements incorporate an independently interpolated linear hydrostatic stress component [20]. The hydrostatic stress is coupled to the constitutive relations by Lagrange multipliers. The use of this type of hybrid element in regions of larger deformation prevents physically unrealistic nodal displacements constraints from propagating through the mesh. In a mesh of standard elements these unrealistic displacement constraints artificially stiffen the deformation response of incompressible or nearly incompressible materials.

A nonlinear static analysis is performed. The analysis includes both geometric and material nonlinearities. Geometric nonlinearity is included to account for large strains and rotations which may occur locally prior to failure. Numerical convergence of the finite element solution is assured independent of structural stability by use of the modified Rik's algorithm available in ABAQUS.

The butt welded plate is subjected to a uniform tensile load in the longitudinal direction. In the finite element evaluation this tensile loading is applied as an uniform longitudinal displacement.

In the present analysis structural failure is considered to be synonymous with fracture initiation. Fracture initiation occurs when the strain energy density reaches the local material toughness.

Discussion of Results

The global load versus normalized displacement response of the butt welded plate is shown in Figure 5. The normalized displacement is δ/L where δ is the longitudinal extension and L is the original length.

Two potentially critical locations with respect to the local toughness occur during the loading history; the edge of the defect and the weld metal-base metal interface. The variation in strain energy density ratios with increasing normalized displacement for these two locations is shown in Figure 6.

Net section yielding occurs across the plate at a normalized displacement of 0.035. After net section yielding, redistribution is observed in the strain energy density fields. Local unloading occurs in the weld crown surround the defect.

At a normalized displacements of 0.044 the critical location with respect to the strain energy density ratio shifts from the edge of the defect to the weld metal-base metal interface.

At a normalized displacement of approximately 0.054 the maximum global load is reached.

The strain energy density contours for a normalized displacement of 0.078 are shown in Figure 7. At this point in the loading history the strain energy density in the weld metal at the weld metal-base metal interface reaches its critical value. The maximum energy density at the edge of the defect remains less than the critical value required for failure. Therefore, failure occurs by fracture at the weld metal-base metal interface and not at the defect.

SUMMARY

The failure criterion used in the current analysis is fracture toughness at the continuum scale. Fracture toughness at the continuum scale is defined using the critical strain energy density at fracture. The critical strain energy density is determined along with the continuum stress-strain relationship from the appropriate interpretation of data obtained from simple laboratory experiments, such as the tensile test. Three-dimensional aspects of the deformation and its influence on the strain energy density are incorporated in the evaluation of test data used to determine the constitutive relationship. For uniaxial material test geometries, the standard Cauchy stress-logarithmic strain curve developed from specimen load-displacement response is not an accurate description of the material constitutive response for large deformations leading to fracture. A more accurate continuum Cauchy stress-logarithmic strain relationship can be developed from the uniaxial data and the percent reduction in area.

In the present analysis the butt welded plate is shown to be insensitive to a weld defect spanning approximately one-third of the crown dimension. The undermatched toughness of the weld material combines with localized deformation to cause failure in the weld metal at the weld metal-base metal interface.

The computational analysis performed does not incorporate a priori assumptions of the location or mode of failure. The continuum basis of the critical strain energy density as a fracture criterion eliminates any need to assume the location of failure.

The results of the analysis suggest that the apparent strength and ductility of weld components, often observed despite the presence of significant defects, is th result of favorable material and geometric interactions. The ability to identify such favorable interactions can be used to identify critical and non-critical defects for subsequent appropriate action.

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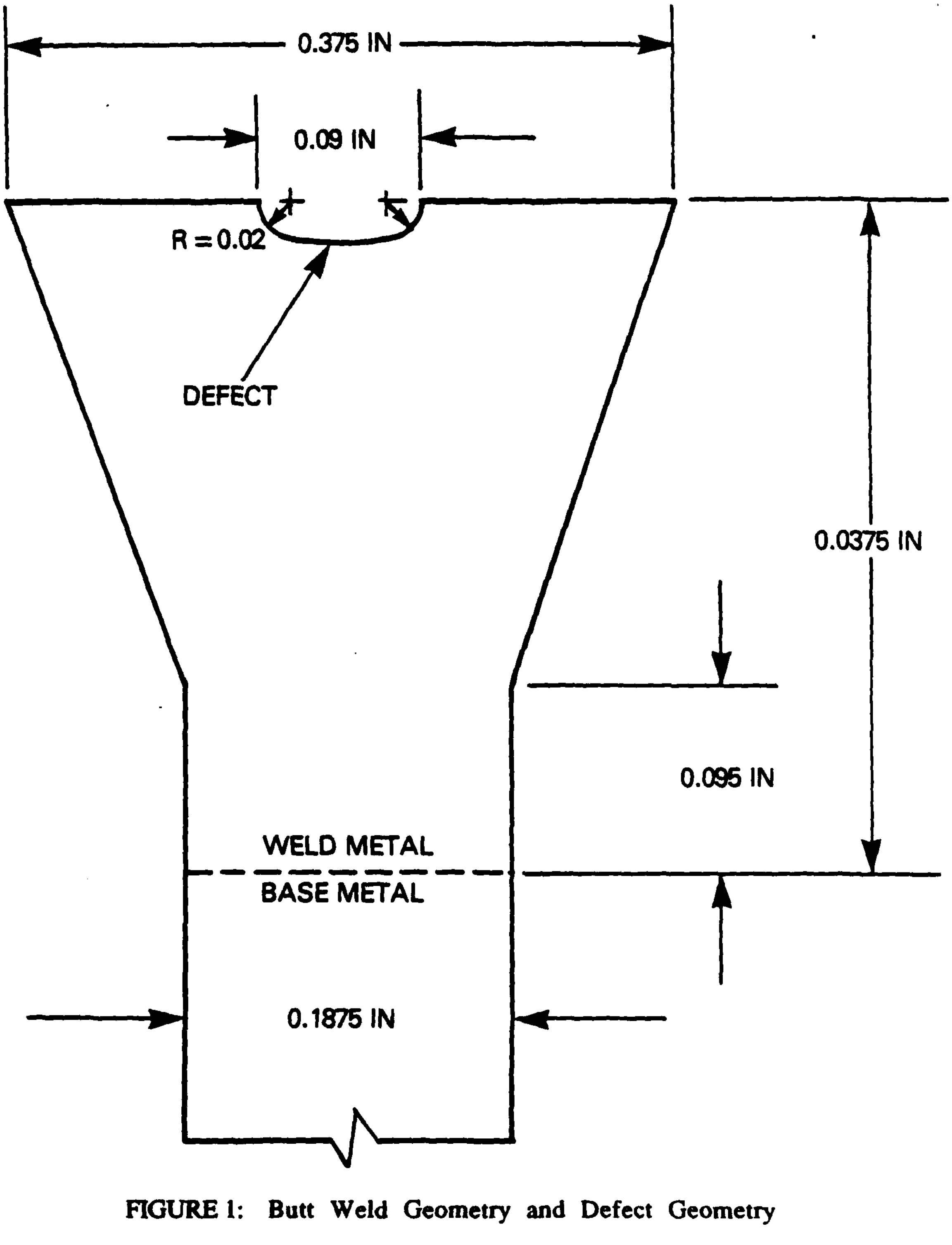


FIGURE 1: Butt Weld Geometry and Defect Geometry

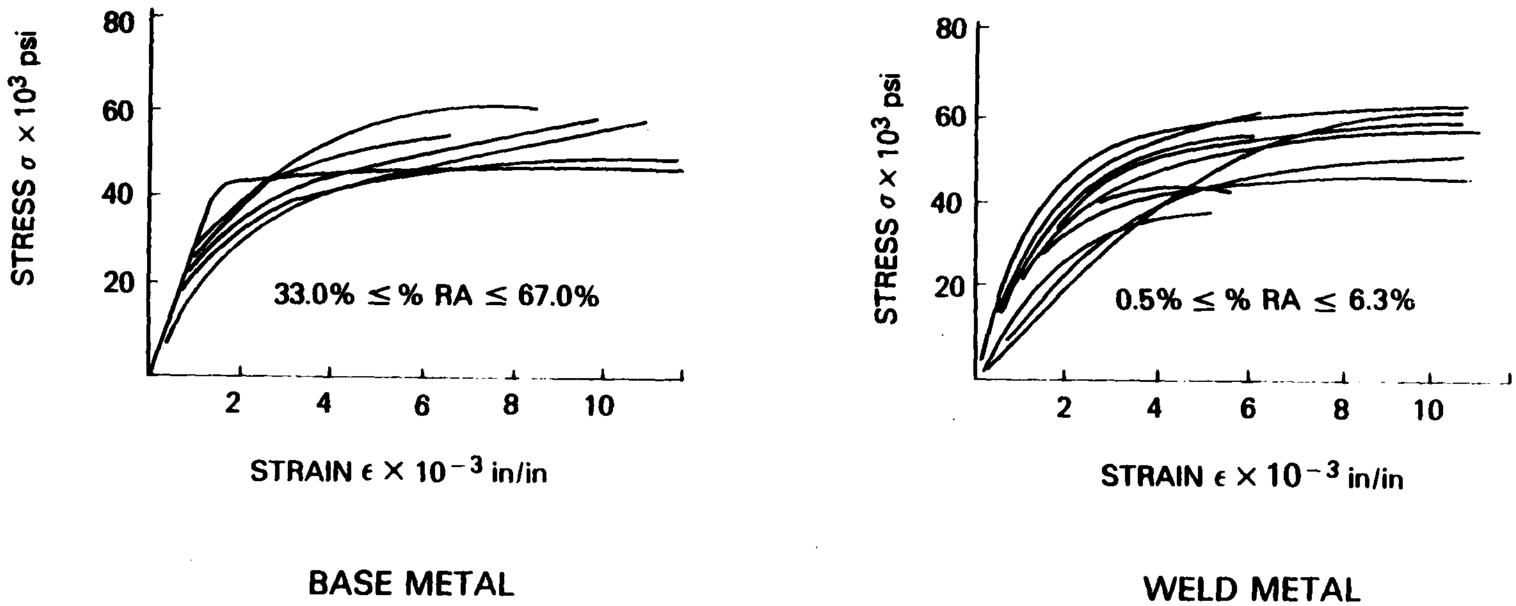


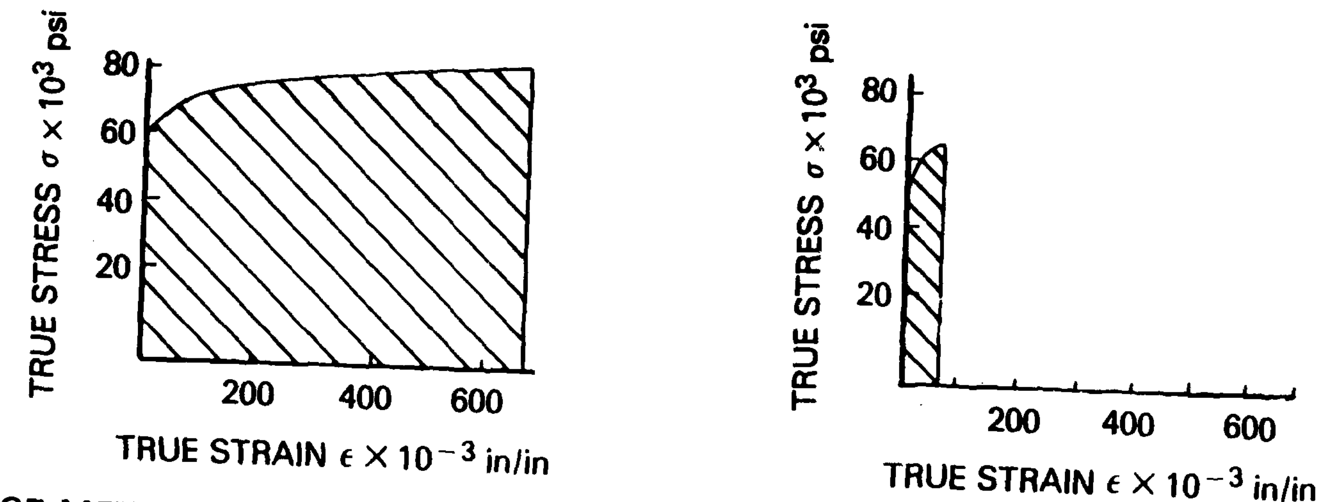
FIGURE 2: Weld Metal and Base Metal Material Response

BASE METAL

$\sigma_Y = 42.7 \times 10^3$ lb/in^2
$\epsilon_y = 0.00122$ in/in
$\sigma_c = 80.0 \times 10^3$ lb/in^2
$\epsilon_c = 0.680$ in/in
$W_c = 54023.$ lb in/in^3

WELD METAL

$\sigma_y = 49.2 \times 10^3$ lb/in^2
$\epsilon_y = 0.00153$ in/in
$\sigma_c = 63.4 \times 10^3$ lb/in^2
$\epsilon_c = 0.0662$ in/in
$W_c = 4087.$ lb in/in^3



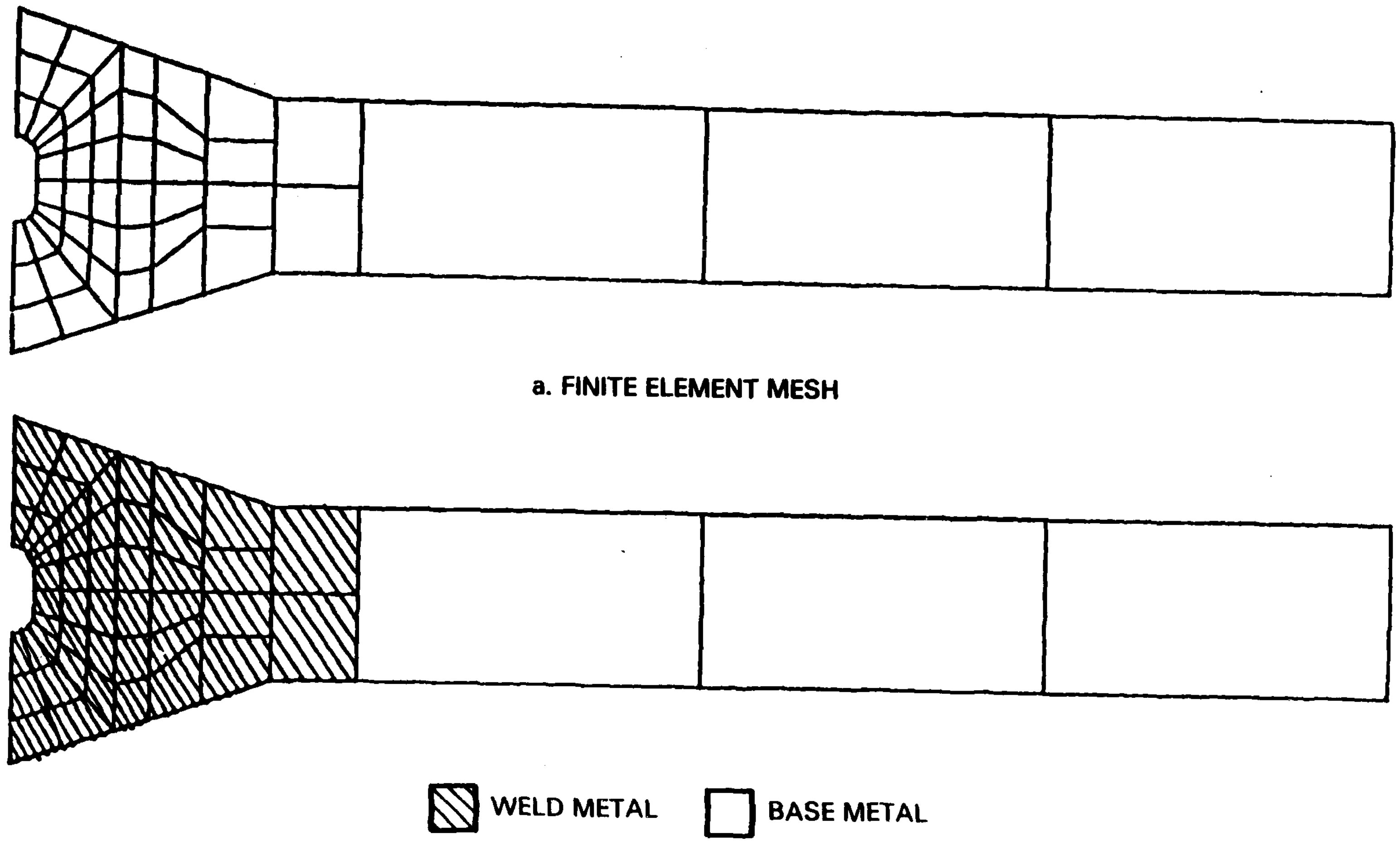
(a) BASE METAL

(HIGH PERCENT REDUCTION OF AREA)

(b) WELD METAL

(LOW PER CENT REDUCTION OF AREA)

FIGURE 3: Weld Metal and Base Metal Cauchy Stress-Logarithmic Strain Response



a. FINITE ELEMENT MESH

b. MATERIAL DEFINITIONS

FIGURE 4: Butt Welded Plate Finite Element Model

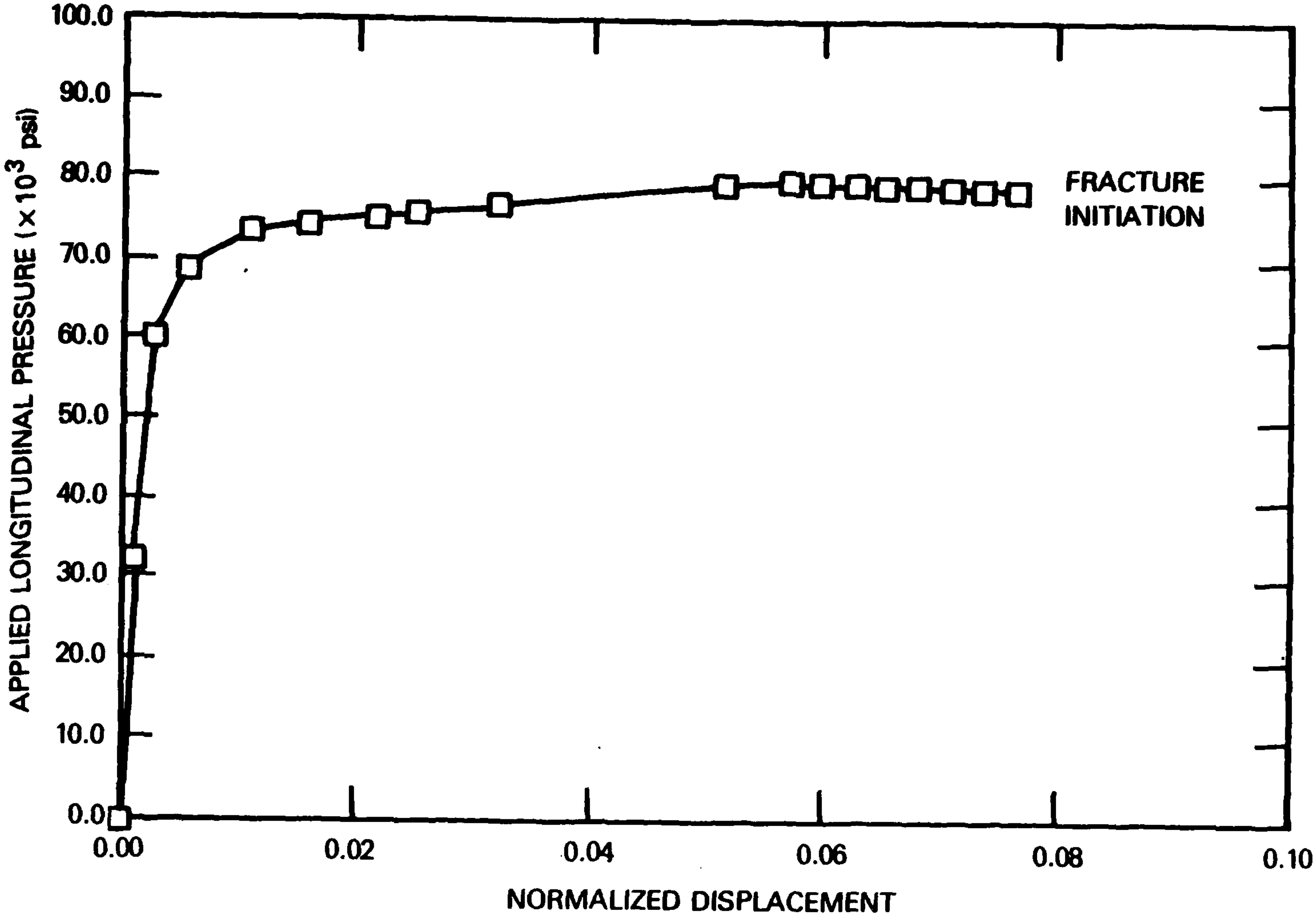


FIGURE 5: Applied Longitudinal Pressure and Normalized Displacement Response

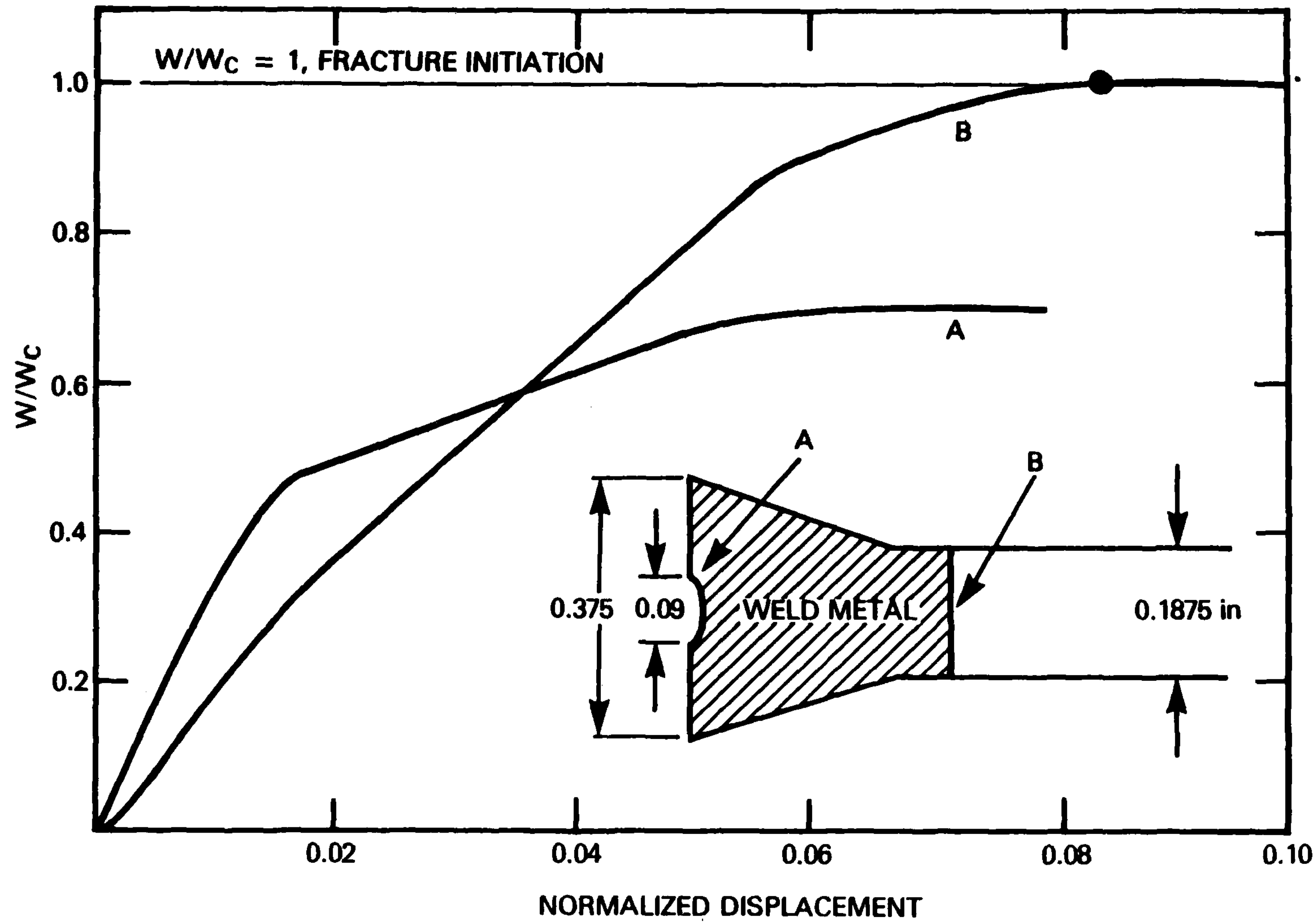
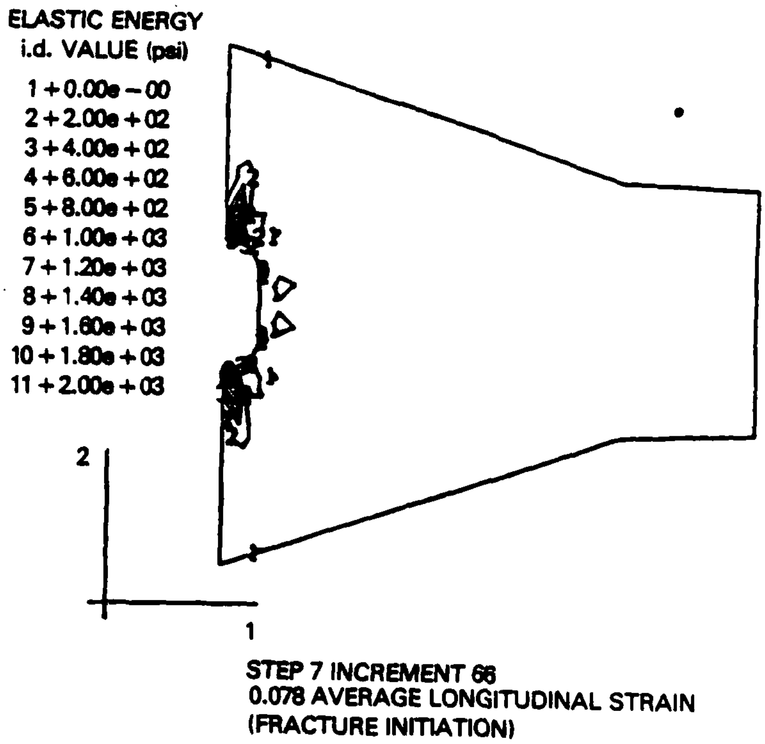


FIGURE 6: Strain Energy Density Ratio for Critical Locations



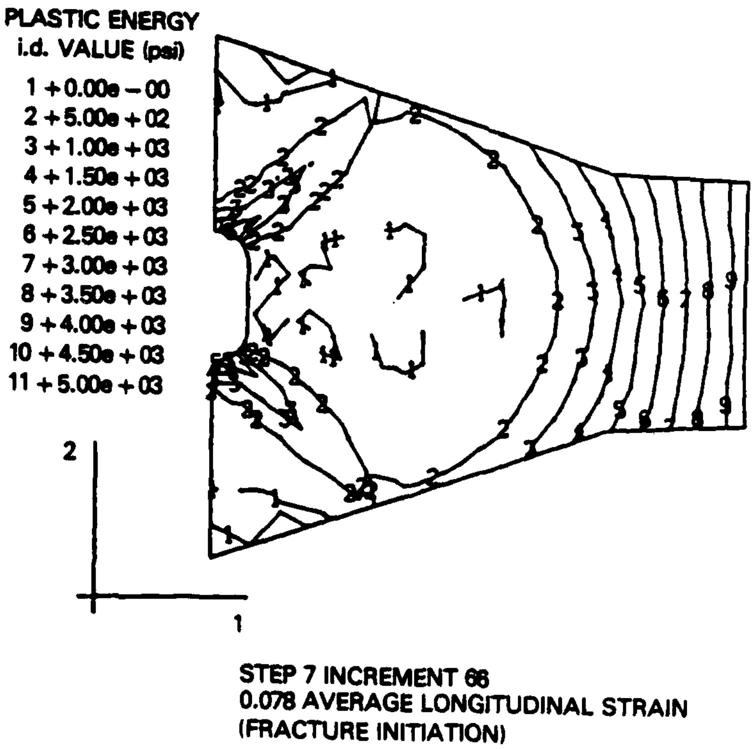


FIGURE 7: Strain Energy Density Contours at 0.078 Normalized Displacement (Fracture Initiation)