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An Experimental – Analytical Comparison of the Ductile Failure of Notched Tensile Bars

Steven E. Benzley, Tommy G. Priddy, James P. Hickerson

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AN EXPERIMENTAL - ANALYTICAL COMPARISON
OF THE DUCTILE FAILURE
OF NOTCHED TENSILE BARS

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ABSTRACT

Experimental results of the ductile failure of 7075-T6 aluminum notched tensile bars are compared with finite strain, nonlinear, finite element calculations. This comparison allows the investigation of mean stress dependent macroscopic theories for ductile fracture. Two such theories are examined and the results are presented in graphical form.

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AN EXPERIMENTAL - ANALYTICAL COMPARISON
OF THE DUCTILE FAILURE
OF NOTCHED TENSILE BARS*

by

S. E. BENZLEY, J. P. HICKERSON, and T. G. PRIDDY

1. INTRODUCTION

Notched tensile bars have several advantages that make them excellent specimens for the study of both the apparent brittle and ductile failure of materials. Among these advantages are: the load application and its effects can be separated from the test region; isotropic material response can be studied with two-dimensional elastic plastic computer programs; the sharpness of the notch can be varied to continuously study the effects of stress tri-axiality; and only uniaxial testing machines are required for load application.

Sharply notched specimens generally fail in a relatively brittle manner, whereas mildly notched specimens generally fail in a ductile mode following a relatively large amount of plastic flow. Mildly notched bars may be analyzed quite accurately by the approximate solution proposed by Bridgeman [1]. However sharply notched specimens are more difficult to analyze because of the extreme strain gradients at the notch tip. These shapes require an accurate, nonlinear, finite strain calculation. An analysis of this kind has been done by Griffiths and Owen [2] for notched bend bars using the finite element approach.

The purpose of this paper is to report some results from recent tests on 7075-T6 notched aluminum bars and to compare these experimental results with finite element calculations. The analytical results are extended for a

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comparison with some previously reported experimental data on 75S-T aluminum alloy notched bars [3]. The computed stress-strain states of the notched bars will be used to investigate two possible macroscopic failure curves as postulated in References [4] and [5].

2. EXPERIMENTAL PROCEDURES

Two types of tests were conducted, tensile tests on hollow tubular specimens shown in Figure 1 and fracture tests on notched round bar specimens shown in Figure 2. Five specimens of each type were tested. The purpose of the hollow tube tests was to provide accurate stress-strain data that could be combined with a finite element analysis and a macroscopic failure theory to predict the deformation and fracture of the notched round bars. The hollow tube design minimized radial strains and provided a geometry more amenable to subsequent analysis than a standard solid round bar.

Each tensile specimen was instrumented with an axial, bending compensated, half bridge, strain gage circuit, and an extensometer of one inch gage length. The strain gages provided accurate strain measurements while the extensometer allowed measurement of total elongation. A spherical ball joint in the loading fixture minimized bending and misalignment in both the tensile and notched round fracture tests.

Notched round bar specimens were instrumented with two opposing extensometers with 1.27 cm (0.500 in.) initial opening. These gages were mounted on the outside diameter of each specimen straddling the machined notch.

Specimens were made from aluminum alloy 7075-T651 and subsequently overaged. Starting material was purchased as a single rod, 3.175 cm (1.250 in.) in diameter, according to Federal Specification QQ-A-225/9B. Overaging was necessary due to the need to apply strain gages with a high elongation adhesive that required a two hour cure at 350°F. The adhesive curing schedule was adopted as the overaging treatment and each group of specimens was heat treated together accordingly. The resulting properties were not unlike those created by the normal T7351 temper of 7075.

3. EXPERIMENTAL RESULTS

The results of the tensile tests are summarized in Figure 3. A large amount of variability is seen in the stress strain curves that cannot be accounted

for at this time. Rockwell B hardness measurements of individual specimens correlated with ultimate tensile strength and ranged in value from $R_B 82$ to $R_B 88$. Similar measurements of notched rounds gave values of $R_B 85$ to $R_B 86$, indicating these to be a much more homogeneous group and probably characterized by stress-strain data near the mean of the curves shown in Figure 3.

Necking was observed in all tensile specimens. Both outer diameters and wall thicknesses were found to decrease, as shown by the measurements given in Table I.

TABLE I. TENSILE SPECIMEN DIMENSIONS
BEFORE AND AFTER TESTING

SPECIMEN	ORIGINAL OUTER DIAMETER cm (in)	AVERAGE FINAL OUTER DIAMETER cm (in)	ORIGINAL WALL THICKNESS cm (in)	FINAL WALL THICKNESS cm (in)
1	1.35 (0.503)	1.09 (0.429)	0.170 (0.067)	0.145 (0.0570)
2	1.35 (0.503)	1.09 (0.430)	0.170 (0.067)	0.144 (0.0565)
3	1.35 (0.503)	1.08 (0.428)	0.170 (0.067)	0.144 (0.0568)
4	1.35 (0.503)	1.10 (0.432)	0.170 (0.067)	0.141 (0.0555)
5	1.35 (0.503)	1.10 (0.432)	0.170 (0.067)	0.141 (0.0555)

The results of notched round bar tests are presented in Figure 4. Two of the five specimens were unloaded first prior to fracture and cross sectioned. The sectioned regions across the notch diameter were carefully polished and examined by optical and scanning electron microscopy at magnifications up to 3000X. No signs of void formation or microcracking were observed except in regions within .007 cm of the notch tip, where several cracked inclusions were located. Similarly, macroscopic features on the fracture surfaces of the remaining three specimens indicated that fracture initiation was probably at the notch root or very near to it.

4. FINITE ELEMENT CALCULATIONS

Finite element analysis of the stress and strain states in sharply notched bars must properly model nonlinear material behavior, large displacements, and

finite strains. The actual procedure used here is patterned after the work of Zienkiewicz and Nayak [6]. The finite element equations are formulated in the Eulerian framework; thusly, the material properties are input as Cauchy (true) stress as a function of logarithmic (true) strain. This formulation is similar to that given by McMeeking and Rice [7]. A correction to the bulk strain constraint given by Nagtegaal, et al, [8] was also included.

5. EXPERIMENTAL/ANALYTICAL COMPARISON NEW DATA

The bounded Cauchy stress-logarithmic strain curves as established by the hollow tube tests reported in Section 2, are shown in Figure 3. The stress-strain data to the onset of necking comes directly from the strain and load gages. This data establishes the curve to point N in Figure 3. Point F of this graph is established from the load and the plastic strain in the necked specimen at failure. Assuming a state of perfect incompressibility at this point, the true effective plastic strain, f_{ϵ}^p , was approximated by

$$f_{\epsilon}^p = f_{\epsilon_{ZZ}}^p = -f_{\epsilon_{rr}}^p - f_{\epsilon_{\theta\theta}}^p \quad (1)$$

where

$$f_{\epsilon_{ZZ}}^p = \text{Axial plastic true strain at failure}$$

$$f_{\epsilon_{rr}}^p = \text{Radial plastic true strain at failure}$$

$$f_{\epsilon_{\theta\theta}}^p = \text{Circumferential plastic true strain at failure.}$$

Note: Averaged values of $f_{\epsilon_{rr}}^p$ and $f_{\epsilon_{\theta\theta}}^p$ through the wall thickness can be obtained from direct measurement of the failed tube, i.e.

$$f_{\epsilon_{rr}}^p \text{ ave} = \ln \left(1 + \frac{\Delta t}{t_o} \right)$$

$$f_{\epsilon_{\theta\theta}}^p \text{ ave} = \ln \left(1 + \frac{\Delta D}{D_o} \right)$$

where

Δt = change in wall thickness

t_o = original wall thickness

ΔD = change in diameter

D_o = original diameter

The stress strain curve is assumed to be linear between point N and F.

The finite element mesh of the notched bar geometry is shown in Figure 4. The element refinement at the notch tip is given in Figure 5. Analytical predictions of applied load versus notch mouth displacement were made using this mesh, the results appearing in Figure 6. Also shown in the figure are the actual measurements made on five test specimens. The two calculated curves given for each specimen result from using upper and lower bound stress-strain data (Figure 3). The two measured curves for each specimen result from using two opposing gages to measure displacements across the notch mouth. Presumably, the differences between the two measured curves for each specimen are due to small misalignments and the average of the two closely approximates ideal behavior. The nonlinearity of these curves signifies that localized yielding has occurred and significant ductility is associated with fracture.

Hancock and McKenzie [5] have tested and analyzed mildly notched bars and compared failure states with a criteria postulated from the work of Rice and Tracey [9]. This criteria is based on the assumption that the effective plastic failure strain, f_{ϵ}^p , is inversely proportional to void growth rate such that

$$f_{\epsilon}^p = \alpha \exp \frac{-3\sigma_m}{2\bar{\sigma}} \quad (2)$$

where

σ_m = mean stress

$\bar{\sigma}$ = effective (von Mises) stress

α = material constant

The constant, α , can be determined from the value of the failure load and strain obtained from the hollow tube tensile tests. Using the maximum and minimum cases, the upper and lower bound failure envelopes are

$$f_{\epsilon_p}^p{}_{upper} = .445 \exp^{-3\sigma_m/2\bar{\sigma}} \quad (3)$$

$$f_{\epsilon_p}^p{}_{lower} = .396 \exp^{-3\sigma_m/2\bar{\sigma}} \quad (4)$$

A plot of these failure envelopes and the computed stress states in the notched cross-section is shown in Figure 8. These results indicate possible failure at any point in the notched specimen from the point on the notch tip to a point* 0.0315 cm interior to the notch tip.

The stress state in a material may also be plotted in the $\sigma_m - \bar{\sigma}$ plane (4). Here a failure envelope which is a function of mean stress may be easily represented. This representation of a postulated failure surface is shown in Figure 9 relative to the computed stress state of the notched tensile bar at failure load. Note the similar situation in both Figures 8 and 9 in that the elements at the notch inward are near both failure models.

*The first seven elements on a line from the notch tip toward the center of the of the specimen are outside of the failure surface of Figure 8.

6. EXPERIMENTAL/ANALYTICAL COMPARISON - HANDBOOK DATA

An extensive series of experiments on notched aluminum bars was done by Aul, Dana, and Sachs [3] and subsequently reported in the Air Force Aerospace Structural Materials Handbook [10]. Their work involved varying notch tip radii from mild to very sharp conditions and also varying the notch depth. A summary of these results is shown in Figure 10.

Finite element calculations were done on notched bars of the shape of Aul's experiments with net section radius - notch tip radius ratios, a/r , of 1.0 and 10.0, and notch depths of 20%, 50%, and 80%. The Cauchy stress logarithmic strain curve for this material, as given by Reference 3, is similar to that of Figure 3. The finite element mesh used for the $a/r = 10$ calculations is analogous to that of Figure 5. A plot of the mesh for $a/r = 1$, 80% notch depth is shown in Figure 11.

A comparison between the experimental and computed results of load as a function of the area reduction, q , is given in Figure 12 where " q " is defined as $1 - A/A_0$ where A is the current cross-sectional area and A_0 is the original cross-sectional area.

To gain an understanding of the failure initiation of these specimens, it is again helpful to study the stress state across the notched section in both σ_m , σ , ϵ^P ; and σ_m , $\bar{\sigma}$ space. These plots are given in Figure 13 and 14 respectively, where the stress state for each shape corresponds to the maximum q as shown in Figure 12. Only a postulated failure envelope of the form of Equation 2 is given for this material in Figure 13 because the value of the effective plastic strain at a known stress state is not readily available from the data in Reference 3. However, Figures 13 and 14 offer some interesting insight concerning the location of the failure initiation as a function of the notch geometry if such a failure envelope were postulated. Figure 13 shows that the 80% notch with an $a/r = 1.0$ will fail at the center of the bar whereas the rest of the specimens would fail at or near the notch tip. Again, the sharply notched specimens have a stress/strain state that is essentially parallel to failure envelope in the immediate region of the notch tip. This situation makes it difficult to predict where the failure initiation will occur, but accounts for sharply notched specimens failing in a "brittle" (sudden) manner and mildly notched specimens failing in a relatively ductile mode.

7. DISCUSSION OF RESULTS

An analytical-numerical comparison of notched tensile bars provides a great deal of information about brittle and ductile failure of a specific material. Mildly notched specimens, such as the 80% notch with $a/r = 1.0$ will tend to fail at the center of the specimen because the $\sigma_m/\bar{\sigma}$ ratio there (i.e., the measure of triaxiality) is relatively high even though the plastic strain at the notched cross-section is relatively low (See Figure 13). The strain state in this specimen is very closely approximated by Bridgeman's solution where a constant strain in the notched section is assumed. (1)

The sharply notched specimens of both the series of tests defined in section 2 and those of Reference 3 should fail at or near the notch tip with a relatively low $\sigma_m/\bar{\sigma}$ vs. ϵ^P plots or σ_m vs $\bar{\sigma}$ plots whether failure of the sharply notched bars initiates at or slightly interior to the notch tip. In both plots, the stress signature lies essentially parallel to the postulated failure envelopes. These observations are summarized in Table II.

Notch	Initial Failure Locus	Specimen Ductility	$\sigma_m/\bar{\sigma}$ At Failure Point	ϵ^P At Failure Point
Sharp	Near Tip	Low	Low	High
Mild	Center	High	High	Low

TABLE II - Comparison on Failure Modes

8. SUMMARY

It is well established that void nucleation, growth, and coalescence strongly depend upon the mean state of stress (i.e., triaxiality) in a material (9, 11). A macroscopic stress-strain failure model founded on the ductile fracture mechanism that is produced by this void growth situation is needed. The ability to accurately formulate and characterize materials with such a model necessarily depends upon the items addressed in this paper, namely: 1) an accurate true stress, finite strain curve of the material; 2) a simple specimen that has an isolated point of void growth tested to both impending and complete failure, and 3) a complete nonlinear stress strain analysis of the specimen. None of these three items is a trivial task yet each can be done if proper care is exercised. For example, tensile tests of thin tubes, as defined in Section 2 of this paper, produce excellent true stress-finite strain curves. Also, Figures 13 and 14 indicate that mildly notched specimens approach postulated failure surfaces at a single (i.e., center of the bar) location whereas sharply notched specimens do not clearly provide an isolated locus of failure. Consequently, the mildly notched tensile bar is an excellent candidate for studying macroscopic failure theories caused by void nucleation growth, and coalescence. Finally, properly formulated nonlinear finite element calculations can provide a complete and accurate macroscopic stress-strain analysis of the problem. Therefore, applying the above procedures on properly selected materials, the establishment of a well-formulated macroscopic failure model, as a function of mean (triaxial) stress, is indeed possible.

A macroscopic failure model based on void growth would provide a much needed tool in the complete analysis necessary for today's critical structures. Such a model could be used to formulate a quasi-static "cumulative" damage finite element formulation similar to that currently being done in dynamic failure calculations (12, 13). This formulation could also be used in establishing low cycle fatigue failure models.

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Fig. 1. The Hollow Tube Specimen

Fig. 3. Upper and Lower Bounds of Experimentally Determined Stress Strain Curves of Overaged 7075-T651 Aluminum

Fig. 4. Finite Element Mesh for Notched Round Bars

Fig. 5. Finite Element Grid Near the Notch Tip

Fig. 6. Load Displacement Curves for Notched Round Bars

— measured data from the two opposing displacement gages
 - - - predicted from upper and lower bound stress-strain curves (Fig. 3)

Fig. 7. Axial Stress (σ_A), Radial Stress (σ_R), and Plastic Strain (ϵ_p) Along the Notch Cross Section

----- upper bound from data in Fig. 3
 ————— lower bound from data in Fig. 3

Fig. 8. Postulated Stress Ratio--Plastic Strain Failure Envelope and Actual Stress State of Notched Cross Sections at Fracture. $\textcircled{T}$ signifies notch tip

Fig. 9. Postulated Effective Stress--Mean Stress Failure Envelope and Actual Stress State of Notched Cross Sections at Fracture

----- upper bound
 ————— lower bound

Fig. 10. Effect of Notch Sharpness and Depth on the Strength of 7075-T6 Bar (Reference 3)

Fig. 11. Finite Element Mesh for Mildly Notched Specimens

Fig. 12. Comparison of Analytical Predictions of Load versus Area Reduction and Experimental Data from Reference 3

— experimental data
 — analytical predictions

Fig. 13. Calculated Stress Ratio versus Plastic Strain for Notched Specimens given in Reference 3. $\odot$ signifies Notch Tip and $\odot$ signifies center of bar.

Fig. 14 Von Mises Stress versus Mean Stress calculated for specimens in Reference 3.

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