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D. P. Jones
J. E. Holliday
L. D. Larson

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BETTIS ATOMIC POWER LABORATORY

WEST MIFFLIN, PENNSYLVANIA 15122-0079

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D. P. Jones

J. E. Holliday

L. D. Larson

Westinghouse Electric Company
A Division of CBS
West Mifflin, PA 15122-0079

ABSTRACT

This paper provides a comparison between test and analysis results for bursting of thin toroidal shells. Testing was done by pressurizing two toroidal shells until failure by bursting. An analytical criterion for bursting is developed based on good agreement between structural instability predicted by large strain-large displacement elastic-plastic finite element analysis and observed burst pressure obtained from test. The failures were characterized by loss of local stability of the membrane section of the shells consistent with the predictions from the finite element analysis. Good agreement between measured and predicted burst pressure suggests that incipient structural instability as calculated by an elastic-plastic finite element analysis is a reasonable way to calculate the bursting pressure of thin membrane structures.

1.0 Introduction

The ability of large strain-large displacement elastic plastic finite element analysis [LS-LD-EP-FEA] to predict the burst pressure of thin toroidal membranes is demonstrated by comparing analysis results to test data. Testing was performed

on two thin toroidal shells made from Alloy 600 material and welded into a high pressure test fixture. The test specimens were hydrostatically pressurized to bursting at room temperature. Test data accumulated during the test consisted of pressure versus torus cross section diametral dilation, burst pressure, identification of failure location and identification of failure mode by fracture surface.

LS-LD-EP-FEA were performed using stress-strain curves representative of the actual materials tested. Analytical failure is defined as the point for which an incremental increase in applied pressure results in a very large (or indeterminate) increase in the torus diameter of the shell. This pressure is called the incipient failure pressure and for these tests, it was 5% larger than the actual burst pressures. The LS-LD-EP-FEA based limiting location is in the membrane section on the inner diameter side of the torus and coincides with the location observed in the tests.

The good agreement between test and analysis in terms of burst pressure, pressure-displacement behavior and failure location demonstrates the ability of LS-LD-EP-FEA to predict the failure of

thin membrane structures without having to resort to artificial limits such as one-half the elastic slope method advocated by the ASME Boiler and Pressure Vessel Code, (1995).

2.0 Testing

A detailed summary of the test phase of this investigation is discussed below. Testing was done by Pressure Services Industries, Inc. for the Westinghouse Bettis Atomic Power Laboratory.

a. Test Fixtures

The test specimens are installed into the test fixture as shown in Figure 1.

b. Specimen Geometry

The specimens tested in this investigation consisted of two thin toroidal shells. The geometry associated with the test specimens is shown in Figure 2. The specimens consist of an inner and an outer half. Each half is welded into a test fixture and the two halves are welded together at the top. The as welded test assembly does not receive a post weld heat treatment or stress relief.

c. Test Instrumentation

Strain gage and displacement measurements were made at various stages of the test right up to failure. Unfortunately, the strain gage data was internally inconsistent and not usable for purposes of qualifying analytical results.

The instrumentation of interest in this particular investigation are the dial gages shown in Figure 1 which measure the radial displacement of the inner and outer membrane portions of the test specimen. The dial gages were calibrated to be accurate to within 0.001 inch (0.0254 mm) and the strain gages to within 10^{-5} in/in.

d. Test Procedure

Burst testing of the toroidal shell was performed by hydrostatically pressurizing the shell in the Figure 2 test assembly from 0 psi to burst at room temperature. Displacement dial gage readings were taken at 500 psi (3.45 N/mm^2) increments from 0 to 12,000 psi (82.7 N/mm^2). Dial gages were removed at 12,000 psi (82.7 N/mm^2) in the interest of safety. For pressures above 12,000 psi (82.7 N/mm^2), the test pressure was slowly increased until failure by bursting occurred. The failure pressure and location of failure were recorded.

e. Test Results

The test results of interest are:

- Failure pressure:
Test specimen 1 - 14,350 psi (98.9 N/mm^2)
Test specimen 2 - 14,400 psi (99.3 N/mm^2)
- Failure location is in the membrane portion of the shell and is located on the inner diameter side of the specimen. The failure location is identified as location A in Figures 1 and 2. The fracture surface, shown in Figure 3, indicates that failure was by ductile rupture.

Pressure-displacement curves from the dial gage readings are presented with the analysis results.

3. Analysis

Details associated with the analytical portion of this study are discussed below.

a. Assumptions

The following assumptions were made in the analysis.

(1) Assumption

The elastic-plastic analysis of the test specimen is conducted assuming an isotropic hardening material law.

Justification

Since the specimens were tested by application of monotonically increasing pressure to failure, there is no reversal of load thus eliminating cyclic hardening concerns. Kinematic or mixed hardening effects are thus limited to very local unloading regions and considered second order for these tests.

(2) Assumption

The residual stress state in the test specimen is not considered in this analysis.

Justification

The residual stress state in the specimen is not considered since residual stress has little effect on ductile rupture and burst at the ultimate state of the material. The reason for this is that loading ductile materials to very large strains will convert residual strains in the specimen to mechanical stresses. At failure in regions of high ductile strain, only the mechanical stresses due to applied loads remain just prior to failure. However, residual stresses will affect distortions. This is born out by the fact that good agreement was found between computed and burst pressure but there could be considerable error in the computed distortion of the shell.

(3) Assumption

The LS-LD-EP-FEA is carried out until the numerical solution becomes unstable, e.g. when a converged solution for an additional increment of load is numerically difficult to obtain. At this point, the slope of the load-displacement curve for the shell becomes vanishingly small. The total pressure that causes this condition is the incipient failure pressure.

Justification

Failure in the test occurs when the shell bursts. Instead of trying to predict local ductile rupture or

tearing from the FEA results, it is proposed here that a useful definition of failure is the pressure for which the structure approaches dimensional instability, i.e. unbounded displacement for a small increment in pressure. This condition is symptomatic of an ill-conditioned boundary value problem caused by the combined changes in geometry and material stiffness leading to a physical instability. This is often preceded by numerical convergence problems. The numerical convergence problem is indicative of impending structural collapse and is characterized by the slope of the load-displacement plot approaching zero. A horizontal load-displacement plot means that the displacement grows unbounded with a small increase in load. The hypothesis of this paper is that the pressure just preceding this numerical instability can be correlated to actual structural collapse and/or material failure by local thinning (or necking down) leading to ductile rupture.

b. Finite Element Model

The geometry analyzed is shown schematically in Figure 1. The as welded geometry is shown in Figure 2.

The finite element model used to conduct the LS-LD-EP-FEA of the test specimens is a two-dimensional (2-D) axisymmetric model and is shown in Figure 4. The finite element model consists of:

- 13,482 Eight node reduced integration quadrilateral elements (CAX8R)
- 41,541 Nodes

c. Material Properties

The material properties used in the LS-LD-EP-FEA of the test specimens are shown in Figure 5.

d. Boundary Conditions

Boundary conditions applied to the FE model are

shown in Figure 4. The boundary of the fixture is assumed to be fixed against all motion. There was no motion of these surfaces observed during the test.

e. Computer Programs

- The LS-LD-EP-FEA was conducted using ABAQUS (1994)
- The FE model shown in Figure 3 was developed using PATRAN (1990).

4. Results

Salient results and comparison to appropriate test data is summarized below:

a. Burst Pressure

The analysis predicts failure at a pressure of 15,043 psi (104 N/mm²) compared to 14,350 (98.9 N/mm²) and 14,400 psi (99.3 N/mm²). The computed value is less than 5% larger than the lowest measured burst pressure.

b. Failure Location and Failure Mode

The specimens failed in the membrane portion of the shell on the inner diameter side of the test specimen as shown schematically in Figures 1 and 2. The fracture surfaces, shown in Figure 3, are consistent with a ductile rupture failure mode.

The analysis predicts failure at the location of maximum average equivalent plastic strain (PEEQ) at the state of incipient failure. A contour plot of this result superposed on an exaggerated displacement plot at failure is shown in Figure 6. From Figure 6 the failure location is observed to occur in the membrane portion of the inner diameter surface of the shell (location A). This location coincides with average through-section PEEQ levels of 21.0% suggesting this is the likely region of ductile rupture.

c. Load-Displacement Response

A comparison of test based and analytically predicted pressure-displacement response of the test specimens is shown in Figure 7. The slope of the pressure-displacement curve from the LS-LD-EP-FEA is approaching zero at 15,043 psi (104 N/mm²) which is within 5% of the observed test burst pressure. Significant error is observed in the distortion of the torus for a given pressure. This error is attributed to the residual stress state.

5. Discussion of Results

Based on a comparison of test data and analysis results the following observations are made:

- Predicted incipient failure pressure is within 5% of measured burst pressures. This suggests that structural instability as calculated by near zero load-displacement slope from LS-LD-EP-FEA can be used to predict bursting of thin toroidal shells.
- The predicted failure location, based on the maximum average PEEQ across the thickness of the test specimen agrees with the observed failure location in the test specimen.
- The analytically based load-displacement response of the test specimen under predicts the measured load-displacement response.
- Neglecting residual stresses in the computations resulted in good agreement for burst pressure, but poor agreement for displacement.

6. Conclusions

The good agreement between calculated and observed burst pressures suggests the following conclusions:

- The calculation of incipient structural instability does not require detailed treatment of the welding residual stress state or consideration of local weld geometry since neither of these were included in the LS-LD-EP-FEA used here.
- The good agreement between predicted and

actual burst pressures suggests that the incipient failure pressure as defined by approaching a zero slope of a calculated load-displacement curve is a practical and reasonable way of estimating burst pressure of thin members.

7. Acknowledgment

The work was performed under a U.S. Department of Energy contract with the Bettis Atomic Power Laboratory, a unit of the Westinghouse Electric Corporation. The experimental portion of this study was designed and followed by Mr. Michael Connelly of the Bettis Atomic Power Laboratory. Actual testing was conducted under a subcontract at Professional Services Industries, Inc.

8. References

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Figure 1. THIN TOROIDAL SHELL BURST TEST SCHEMATIC AND INSTRUMENTATION DIAGRAM

Figure 2. THIN TOROIDAL SHELL BURST TEST - AS WELDED GEOMETRY

Figure 3. THIN TOROIDAL SHELL BURST TEST - IDENTIFICATION OF BURST SITE AND FRACTURE SURFACE

Figure 4. THIN TOROIDAL SHELL BURST TEST ANALYSIS - FINITE ELEMENT MODEL AND BOUNDARY CONDITIONS

Figure 5. THIN TOROIDAL SHELL BURST TEST ANALYSIS - MATERIAL PROPERTIES

Figure 6. THIN TOROIDAL SHELL BURST TEST ANALYSIS - EQUIVALENT PLASTIC STRAIN AT POINT OF INCIPEINT ANALYTICALLY PREDICTED FAILURE

Figure 7. THIN TOROIDAL SHELL ANALYSIS - PRESSURE VERSUS DIAMETRAL DILATION

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