EXPERIMENTAL AND ANALYTICAL
INVESTIGATIONS OF THE
STRUCTURAL BEHAVIOR OF
NOZZLE-TO-SHELL ATTACHMENTS

J. P. Callahan
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MASTER

OAK RIDGE NATIONAL LABORATORY

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BEHAVIOR OF NOZZLE-TO-SHELL ATTACHMENTS

J. P. Callahan W. L. Greenstreet

AUGUST 1973

NOTICE

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NOMENCLATURE

A	cross-sectional area of reinforcing
A_f	cross-sectional area of reinforcing provided by the fillet
a	inside radius of shell
C	couple loading of straight pipe
C_i	in-plane couple on branch
C_o	out-of-plane couple on branch
d	diameter of nozzle or hole
D	diameter of shell
k	length of flattened portion of acute corner of oblique hole in a flat plate
L	length of nozzle
P	internal pressure
r	radius of nozzle, radius of the rounded acute corner of oblique hole in a flat plate
R	radius of shell
s	nominal stress in nozzle*
S	nominal stress in shell*
t	thickness of nozzle
t'	thickness of nozzle with uniform wall reinforcing
T	thickness of shell
T'	thickness of shell with uniform wall reinforcing on shell
α	hillside angle
γ	lateral angle
$\emptyset$	fillet radius
$\emptyset_3$	fillet radius at intersection of triangular pad with nozzle
$\emptyset_4$	fillet radius at intersection of triangular pad with shell
$\emptyset_A$	external fillet radius on crotch for nozzle angles $\geq 90^\circ$
$\emptyset_o$	external fillet radius on crotch for angles $\leq 90^\circ$

*Membrane stresses for pressure P only; these are given as follows:

$$\begin{aligned}
 s &= Pd/2t \text{ for nozzle,} \\
 S &= PD/2T \text{ for cylinder,} \\
 S &= PD/4T \text{ for sphere.}
 \end{aligned}$$

ν Poisson's ratio

ρ_o mean radius of nozzle

$\beta = [3(1 - \nu^2)]^{1/4} (r_m t)^{-1/2}$, for nozzle

$\beta = [3(1 - \nu^2)]^{1/4} [2(RT)^{-1/2}]$, for shell

Ω nozzle-to-shell attachment angle

θ acute angle of intersection of reinforcement pad with nozzle

Subscripts

o outside

i inside

m mean

EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS OF THE STRUCTURAL BEHAVIOR OF NOZZLE-TO-SHELL ATTACHMENTS

J. P. Callahan W. L. Greenstreet

ABSTRACT

Experimental and analytical investigations of nozzle-to-shell attachments are being made under the general sponsorship of the U.S. Atomic Energy Commission and the Pressure Vessel Research Committee of the Welding Research Council. The Oak Ridge National Laboratory is the coordinating organization for this program. The objectives of the program are the development and verification of methods of analysis for various types of reinforced and unreinforced openings in pressure vessels, the performance of experimental and analytical studies of these openings, and the preparation of the resulting information in forms suitable for code-rule development. The studies encompass elastic and plastic behavior of individual openings and elastic behavior of closely spaced multiple openings. Participants in the studies include 11 independent organizations at 7 separate institutions. The purpose of this report is to describe the investigations and to identify program participants. To this end, the report covers the organization of the program, the work undertaken by each participating organization, and the work remaining to be done. Listings of technical reports and papers which describe results obtained from the studies are included.

Keywords: nozzle-to-shell attachments, elastic behavior, plastic behavior, single nozzles, multiple nozzles, experimental, analytical.

INTRODUCTION

The region of intersection of a nozzle with a pressure vessel is generally one in which high stresses exist. Consequently, the designer of a pressure vessel must have means for accurately predicting the magnitudes and locations of maximum stresses in these regions. In addition, the designer must be able to predict plastic limit loads for nozzle-to-vessel attachments to prevent excessive distortion or, in extreme cases, plastic

collapse during extended periods of vessel operation. The ORNL Nozzles Program has undertaken the development and verification of analytical procedures capable of identifying these critical conditions. Included in the program are studies of single nozzles attached either radially or non-radially to spherical shells, perforated flat plates and spherical shells, clusters of nozzles attached to flat plates and spherical shells, and nozzles attached to cylindrical shells. These geometries have been selected to provide the information required to develop basic understanding of stress-strain behavior and to provide the basis for the systematic development of analytical methods.

To complement the analytical methods development, each study includes an experimental phase designed to supply highly reliable data for use in verifying the candidate analyses. Other factors to be investigated include the effect of superposition of various loadings on the nozzle, mutual interactions between adjacent openings and nozzles, and the relationship of information resulting from this program to current design practice. The findings of these studies are not limited in application to the nuclear industry; they are applicable to pressure vessel technology in general.

The program is divided into a cooperative effort between the AEC (ORNL) and industry under the auspices of the Pressure Vessel Research Committee (PVRC) of the Welding Research Council and an effort sponsored solely by the AEC (ORNL). The work is listed in Tables 1 and 2 according to types of openings and model configurations. Emphasis of the joint AEC-PVRC effort is on the single nozzles and openings, while the AEC (ORNL) effort is concerned primarily with closely spaced clusters of nozzles and holes. Also indicated in the tables are the experimental models and analytical methods employed as well as the type of behavior (elastic or plastic) being studied.

Loadings of principal interest are internal pressure and externally applied nozzle loadings consisting of axial force and torsional and bending moments. These loadings are listed in Tables 1 and 2, with the specific test loadings denoted by an I for models having idealized configurations and by an R for models having reinforced configurations.

Table 1. Analytical and experimental investigations of nozzle attachments sponsored by AEC (ORNL) and the FVRC

Opening	Shell or plate	Type of study	Method of analysis	Experimental model	Applied loadings				Status of work
					Internal pressure	External loads	Combined	Thermal	
Radial nozzle	Cylinder	Elastic	Thin shell ^a Finite element		I ^b	I		I	Under development
					I	I		I	Being verified
				Strain-gaged steel	I	I			In progress ^c
				Strain-gaged steel	R ^d	R			FVRC and others ^e
				Photoelastic	R				Completed
	Sphere	Elastic	Thin shell ^a Finite element Other numerical methods		I	I		I	Completed
					I, R	I, R		I, R	Verified for pressure
					I, R	I, R			Partially verified
				Strain-gaged steel	I	I			Essentially completed
				Strain-gaged steel	R	R			FVRC and others ^e
				Photoelastic	I, R				FVRC and others
	Cylinder	Plastic collapse	Lower and upper bound limit		I, R	I, R	I, R		Under development
				Steel	I	I			Partially completed
	Sphere	Plastic collapse	Lower and upper bound limit						
				Steel	I	I	I		Completed
Nonradial nozzle	Cylinder	Elastic		Strain-gaged steel		I			Completed
				Photoelastic	I				Completed
	Sphere	Elastic	Thin shell ^a		I				Being verified
				Strain-gaged steel	I	I			In progress ^f
				Photoelastic	I, R				Completed
	Cylinder	Plastic collapse	Upper bound limit loads		I, R	I, R			Under development
				Steel	I	I			Partially completed
Nonradial holes	Cylinder	Elastic		Photoelastic	I				Completed
	Sphere	Elastic		Photoelastic	I				Completed
Skewed holes	Flat plate	Elastic	Closed form type			I ^g			Completed
		Elastic ^h		Steel		I ^g			Completed
		Plastic		Steel		I ^g			Completed
Closely spaced nozzles	Cylinder	Elastic		Photoelastic	R				Completed

^aClosed-form type solutions.

^bIdealized configuration.

^cThree of four models completed.

^dReinforced configuration.

^eNumerous models have been examined in FVRC-sponsored studies as well as other studies.

^fTesting of the last of the planned 22 1/2° nonradial nozzle configurations is under way; the 45° nonradial nozzle is being fabricated.

^gIn-plane edge loads.

^hContinuation of elastic studies, not part of joint AEC-FVRC program.

Table 2. AEC-sponsored analytical and experimental investigations of multiple nozzles

Opening	Shell or plate	Type of study	Method of analysis	Experimental model	Applied loadings				Status of work
					Internal pressure	External loads	Combined	Thermal	
Closely spaced holes	Flat plate	Elastic	Numerical (point matching)		I ^{a,b}				Completed
Closely spaced nonradial holes	Sphere			Strain-gaged steel		I ^{a,b}			Completed
				Strain-gaged steel	I				Completed
Closely spaced nozzles	Flat plate	Elastic	Numerical (point matching)		I ^{b,c}	I			Under development ^c
	Sphere			Strain-gaged steel	I ^b	I			In progress
				Strain-gaged steel	I	I			In progress

^aIdealized configuration.

^bSimulated by biaxial in-plane edge forces.

^cDevelopment completed for one and two nozzles, and partially completed for five nozzles.

Model parameters being studied include nozzle-to-shell diameter ratios (d/D) and diameter-to-thickness ratios of the nozzle (d/t) and of the shell (D/T),* nozzle-to-shell attachment angle (Ω), and nozzle internal protrusion length (L_i). The multiple-nozzle studies also take into consideration the number, pattern, and spacing of nozzles.

The research is being conducted at the various universities and research laboratories listed in Table 3, along with a brief description of each activity, the sponsoring agency, and the current status. All of the activities are under the general sponsorship of the AEC and PVRC, with some support from other organizations.

ORNL, in addition to active participation in the research in the areas listed in Table 3, has also been assigned the tasks of coordination, review, and evaluation of the program for the PVRC Subcommittee on Reinforced Openings and External Loadings. This management function includes (1) directing AEC-sponsored work, (2) preparing reports and recommendations to the PVRC subcommittee on non-AEC sponsored projects, and (3) soliciting recommendations from the subcommittee on AEC-sponsored work. In addition, ORNL conducts analytical and experimental studies in support of the total program as the need arises.

This report describes each investigation and reports the status of the work through the end of FY 1972 (June 30, 1972) for AEC (ORNL)-sponsored studies and through September 30, 1972, for PVRC-sponsored work. Also summarized is the AEC (ORNL)-sponsored work planned for FY 1973 and the PVRC-supported studies to be conducted during the period between October 1, 1972, and September 30, 1973. More detailed information on completed portions of the work is available from the topical reports listed at the end of each individual study summary. Two earlier documents describing this program are:

1. W. L. Greenstreet and R. C. Gwaltney, Experimental and Analytical Investigations of the Structural Behavior of Nozzle-to-Shell Attachments, ORNL-TM-2526 (April 1969).

*In some of the studies an equivalent set of dimensional parameters consisting of d/D , D/T , and s/S are specified, where s and S are nominal membrane stresses in the nozzle and shell, respectively, due to internal pressure.

Table 3. Current experimental and analytical investigations of nozzle attachments

Program sponsor	Funding agency	Subcontractor	Program	Status
AEC-PVRC	AEC	University of Tennessee - I	Experimental stress analysis of single radial and nonradial nozzles attached to spherical shells subjected to internal pressure, thrust, shear, torsional, and moment loadings; plastic collapse of thin-walled cylindrical steel model	In progress
	AEC	Westinghouse Research Laboratories	Photoelastic studies of radial and nonradial nozzles attached to spherical and cylindrical shells and closely spaced pairs of reinforced nozzles attached to cylindrical shells under internal pressure loading	Completed
	AEC	Oak Ridge National Laboratory	Experimental stress analysis of single nozzles attached to cylindrical shells under 13 loadings and development of analytical solutions for internal pressure and moment loadings	In progress
	AEC	Auburn University - II	Theoretical solution for single nonradial nozzles attached to a spherical shell at angles of obliquity less than 20° for internal pressure loading	Completed
	AEC	Oak Ridge National Laboratory	Expansion of present theoretical solution of single non-radial nozzle attached to a spherical shell to include angles of obliquity greater than 20° and for nozzle loadings	In progress
	PVRC, NRCC ^a	University of Waterloo	Analytical methods development of upper bounds to limit pressures, moments, torques, and forces, applied either separately or in combinations, to radial or nonradial nozzles attached to cylindrical shells and experimental studies of tees and laterals to provide data for analysis verification	In progress
	PVRC, NRCC ^a	University of Sherbrooke	Analytical methods development for calculating lower bounds to limit loads for cylindrical shells with radially and non-radially attached nozzles where the composite structure is subjected to internal pressure or external loadings on the nozzle or combinations of internal pressure and external loads, and use of resulting analyses in parameter studies; limited experimental studies in support of limit-load analysis development	In progress

Table 3 (continued)

Program sponsor	Funding agency	Subcontractor	Program	Status
	NRCC ^a	University of Sherbrooke	Analytical and experimental studies of plastic redistribution of stresses around oblique holes in flat plates subjected to uniaxial tension, and experimental study of the effect of corner cut on elastic stress concentration for oblique holes in flat plates	Completed
	AEC	Oak Ridge National Laboratory	Finite-element studies of reinforcement configurations for spherical shells and shell attachment regions	In progress
			Analyses of models using recently developed computer programs and comparisons between analytical and experimental results	In progress
			Parametric studies for program guidance and code use	In progress
	AEC	Battelle Memorial Institute - I	Engineering evaluation and correlation of results for nozzle-to-shell attachments and preparation of material based on these results for use in support of ASME code committee work	In progress
AEC (ORNL)	AEC	University of Tennessee - II	Experimental stress analysis of flat plates with clusters of holes	Completed
	AEC	Auburn University - I	Experimental stress analysis of spherical shells with clusters of nozzles and holes	In progress
			Experimental stress analysis of flat plates with clusters of nozzles	In progress
	AEC	Battelle Memorial Institute - II	Theoretical methods development for flat plates with clusters of holes	Completed
			Theoretical methods development for flat plates with attached clusters of nozzles	In progress

^a National Research Council of Canada.

2. W. L. Greenstreet and R. C. Gwaltney, Addendum - Experimental and Analytical Investigations of the Structural Behavior of Nozzle-to-Shell Attachments, ORNL-TM-2526, Addendum (November 1970).

Summaries of results obtained are described in:

1. W. L. Greenstreet, S. E. Moore, and R. C. Gwaltney, Progress Report on Studies in Applied Solid Mechanics, ORNL-4576 (August 1970).
2. W. L. Greenstreet, S. E. Moore, and J. P. Callahan, Second Annual Progress Report on Studies in Applied Solid Mechanics (Nuclear Safety), ORNL-4693 (July 1971).
3. W. L. Greenstreet, S. E. Moore, and J. P. Callahan, Third Annual Progress Report on Studies in Applied Solid Mechanics (Nuclear Safety), ORNL-4821 (December 1972).

PART 1. AEC (ORNL)-PVRC COOPERATIVE PROGRAM

The primary objectives of this program are (1) to develop design rules and theoretical analysis methods for various types of single nozzles attached to either cylindrical or spherical vessels and (2) to perform experimental studies to provide reliable data for empirical correlations and for verifying the analyses. The program also includes an experimental study of closely spaced pairs of nozzles and analytical parameter studies using the methods developed under this program. An additional task of this program is to prepare the information developed by the overall nozzles program and others in forms suitable for use in the pressure vessel design codes and standards.

This section summarizes the work being done by the participating organizations under joint AEC (ORNL)-PVRC sponsorship. For the reader's convenience, each summary presents (in order) the objective, the types of models being studied, the scope of the program, the progress through FY 1972, and the work planned for FY 1973. In the cases of PVRC-supported work the progress reported is for the period through September 30, 1972, and the work planned is for the period between October 1, 1972, and September 30, 1973.

University of Tennessee - I

Principal Investigators: R. L. Maxwell and R. W. Holland

Objective

Work at the University of Tennessee is focused on the experimental stress analysis of individual nozzles attached radially or nonradially to hemispherical shells. Major emphasis of the work is on nonradial nozzles, but additional tests are performed as specific needs are identified. The data generated through these tests are used primarily in the development and verification of methods of analysis of single nozzle-to-spherical shell attachments.

Description of Models

The models are accurately machined steel hemispheres having a middle surface radius of 15 1/4 in. and a wall thickness of 3/8 in. The individual nozzles are attached either radially or nonradially to the hemispheres using full penetration welds, with the resulting fillets between the nozzle and shell being reduced to essentially a zero radius by grinding and hand filing. Each model is extensively instrumented with approximately 600 foil-type electrical resistance strain gages. Included in the study are nozzles with outside diameters of 2 5/8 and 7 7/8 in., as listed in Table 4. The 2 5/8-in. nozzles have attachment angles of 0 (radial nozzle), 22 1/2, and 45°, as measured between the longitudinal axis of the nozzle and normal to the surface of the shell; the 7 7/8-in. nozzles are attached at angles of 0 and 45°.

Scope

Initially each nozzle is fabricated with a relatively thick wall. Upon completion of a planned series of loadings, the wall thickness of the nozzle is reduced and the loading series repeated. In addition, each nozzle, except TS 807-451 (Table 4), is fabricated with an internal protrusion. The length of both the nozzle and its internal protrusion is designed to allow juncture discontinuity stresses to be attenuated within the length of each portion. After the nozzle has been reduced to its final thickness, the internal protrusion is shortened in steps, and the test series is repeated until the nozzle is made flush with the vessel inside surface.

A single loading series may consist of internal pressure and nozzle loadings of axial thrust, a bending moment, a shearing force applied normal to the nozzle at its juncture, and possibly a torsional or twisting moment. The scope of each test series is subject to modification depending upon the results obtained.

The nozzle configurations that comprise the series used in the program are listed in Table 4. The model numbers listed in the table follow the basic designation system recommended by the FVRC Subcommittee on Reinforced Openings and External Loadings. The initial letter indicates the

Table 4. University of Tennessee single radial and nonradial nozzle-to-spherical shell configurations

All nozzles are attached to spherical shells having an outside diameter, $D_o = 30.88$ in.; an inside diameter, $D_i = 30.13$ in., and wall thickness, $T = 0.375$ in.

Model designation	Dimensions ^a (in.)					
	L_o	L_i	d_o	d_i	t	r_m
7.875-in.-OD radial nozzle						
TS 807-001	14.0	10.0	7.875	7.125	0.375	3.75
TS 807-002	14.0	10.0	7.875	7.500	0.187	3.84
TS 807-003 ^{b, c}	14.0	0.0	7.875	7.500	0.187	3.84
7.875-in.-OD 45° nozzle						
TS 807-451 ^{c, d}	14.0	0.0	7.875	7.125	0.375	3.75
2.625-in.-OD radial nozzle						
TS 802-001	8.5	4.0	2.625	2.125	0.25	1.19
TS 802-002	8.5	4.0	2.625	2.375	0.125	1.25
TS 802-003	8.5	0.75	2.625	2.375	0.125	1.25
TS 802-004	8.5	0.375	2.625	2.375	0.125	1.25
TS 802-005	8.5	0.0	2.625	2.5	0.0625	1.28
2.625-in.-OD 22 1/2° nozzle						
TS 802-221	8.5	4.0	2.625	2.125	0.25	1.19
TS 802-222	8.5	4.0	2.625	2.500	0.0625	1.28
TS 802-223 ^{b, c}	8.5	0.0	2.625	2.500	0.0625	1.28

^a L_o = nozzle extension outside dome; L_i = nozzle extension inside dome; d_o = outside diameter of nozzle; d_i = inside diameter of nozzle; t = wall thickness of nozzle; r_m = midsurface radius of nozzle.

^bConfigurations being prepared for testing.

^cUntested configurations.

^dConfigurations being fabricated.

test site, which is the University of Tennessee (T), and the second letter describes the basic geometry of the vessel, which is a sphere (S). Of the six integers used the first two specify the shell diameter to thickness (D/T) ratio; the third indicates the nozzle outer diameter; the fourth and fifth indicate the angle of inclination of the nozzle; and the final integer is the model number. For example, the first model listed in Table 4, TS 807-001, is the initial configuration of a sphere having a D/T ratio of 80.35 and a 7 7/8-in.-OD radial (indicated by 00) nozzle. Table 5 lists the dimensionless parameter ratios for each model.

Accomplishments

The status of each model is indicated in Table 4 by footnotes. Testing has been completed for all models without footnote designations; included are all configurations of the 2.625-in.-OD radial nozzle and the first two configurations of both the 7 7/8-in.-OD radial nozzle and the 2 5/8-in.-OD, 22 1/2° nonradial nozzle. The latter two models are currently being modified by removing the internal protrusions to form models 807-003 and 802-223 respectively.

A computer program has been developed under this program (5)* for reducing and plotting experimental data in the PVRC-recommended form. This program provides a rapid and efficient method for handling data from tests involving large numbers of data points. The plots of stress versus model profile that are generated by a cathode ray tube (CRT) plotter can be used without modification in the final reports. The data are also typed in tabular form by computer directly onto the reproduction mats.

In addition to the tests listed in Table 4, an internal pressure collapse test was conducted on a thin-walled cylindrical shell with a single radial nozzle attachment having a shell diameter-to-thickness ratio $D_o/T = 230$, a nozzle-to-shell diameter ratio $d_o/D_o = 0.5$, and a calculated hoop stress ratio $s/S = 0.51$. This particular model, model C-1, was

*Numbers in parentheses refer to the correspondingly numbered project report listed at the end of the section.

Table 5. University of Tennessee single radial and nonradial
nozzle-to-spherical shell model parameters^a

Model designation	r_m/t	T/t	R_m/r_m^a	β	βL_o	D_i/T	d_i/t	d_i/D_i	t/T	D_o/d_o	s/S
TS 807-001	10.0	1.00	4.07	1.078	10.78	80.35	19.0	0.236	1.00	3.92	0.491
TS 807-002	20.5	2.00	3.97	1.964	19.64	80.35	40.0	0.249	0.50	3.92	1.007
TS 807-003	20.5	2.00	3.97	1.964	19.64	80.35	40.0	0.249	0.50	3.92	1.007
TS 807-451	10.0	1.00	4.07	1.078	10.78	80.35	19.0	0.236	1.00	3.92	0.491
TS 802-001	4.75	1.50	12.85	2.350	9.40	80.35	8.5	0.071	0.67	11.77	0.233
TS 802-002	10.00	3.00	12.20	3.240	12.96	80.35	19.0	0.079	0.33	11.77	0.491
TS 802-003	10.00	3.00	12.20	3.240	12.96	80.35	19.0	0.079	0.33	11.77	0.491
TS 802-004	10.00	3.00	12.20	3.240	12.96	80.35	19.0	0.079	0.33	11.77	0.491
TS 802-005	20.50	6.00	11.91	4.550	18.20	80.35	40.0	0.083	0.17	11.77	1.007
TS 802-221	4.75	1.50	12.85	2.350	9.40	80.35	8.5	0.071	0.67	11.77	0.233
TS 802-222	20.50	6.00	11.91	4.550	18.20	80.35	40.0	0.083	0.17	11.77	1.007
TS 802-223	20.50	6.00	11.91	4.550	18.20	80.35	40.0	0.083	0.17	11.77	1.007

^a R_m = mean radius of shell; r_m = mean radius of nozzle; $\beta = [3(1 - \nu^2)]^{1/4} (r_m t)^{-1/2}$;
 s/S = nozzle-to-shell nominal membrane stress ratio (Dt/dT) for internal pressure loading.
 See Table 4 for definition of all other terms.

originally tested elastically at the Illinois Institute of Technology Research Institute.*

Work Planned

The modification of model 802-222 will be completed during FY 1973. This modification consists in removing the 4-in. internal protrusion and replacing the damaged strain gages, thereby forming model 802-223. This new 22 1/2° nonradial nozzle configuration will then be tested under the planned loadings consisting of axial thrust, torsion, and various bending moments applied to the nozzle as well as internal pressure. Reports containing the results of these tests will be prepared. Fabrication of model 807-451 is also scheduled for completion during FY 1973, and the installation of strain-gage instrumentation should also be completed.

Model 807-003, the final radial nozzle configuration to be tested, was formed by removing the internal protrusion of model 807-002. All strain gages disturbed by the modification will be replaced, and the model will be prepared for testing. This model has been assigned a low priority so that testing of nonradial nozzle models may proceed as rapidly as possible. It is anticipated that testing of this model will be initiated during FY 1973. Finally, the report (9) containing the results of the internal pressure collapse test of the cylindrical pressure vessel will be published.

Project Reports

1. R. L. Maxwell, R. W. Holland, and J. A. Cofer, Experimental Stress Analysis of the Attachment Region of Hemispherical Shells with Radially Attached Nozzles, Report ME-7-65-1, University of Tennessee (June 1965).
2. R. L. Maxwell and R. W. Holland, Experimental Stress Analysis of the Attachment Region of Hemispherical Shells with Radially Attached Nozzles, Part 2. Radial Nozzle, 7.875 O.D. - 7.125 I.D., 10.0 in. Penetration, Report ME-7-67-1, University of Tennessee (April 1967).

*W. F. Riley, Experimental Determination of Stress Distributions in Thin Walled Cylindrical and Spherical Pressure Vessels, Bulletin No. 108, Welding Research Council, September 1965.

3. F. J. Witt, R. C. Gwaltney, R. L. Maxwell, and R. W. Holland, "A Comparison of Theoretical and Experimental Results from Spherical Shells with a Single Radially Attached Nozzle," Trans. ASME, J. Eng. Power 89(3), 333-40 (July 1967).
4. R. L. Maxwell, R. W. Holland, and G. R. Stengl, Experimental Stress Analysis of the Attachment Region of Hemispherical Shells with Attached Nozzles, Part 3a, Part 3b, Part 3b (continued), Part 3c, Non-radial Nozzle at 22 1/2 Degrees, 2.625 O.D. - 2.125 I.D., 4.00 in. Penetration, Report ME-7-69-1, University of Tennessee (April 1969).
5. G. R. Stengl, A Computer Program for the Generation of Stress Versus Profile Drawings, Report ME-7-70-3, University of Tennessee (June 1970).
6. R. L. Maxwell, R. W. Holland, and G. R. Stengl, Experimental Stress Analysis of the Attachment Region of Hemispherical Shells with Attached Nozzles, Part 2b, Radial Nozzle, 7.875 O.D. - 7.500 I.D., 10.00 in. Penetration, Report ME-7-70-1, University of Tennessee (June 1970).
7. R. L. Maxwell, R. W. Holland, and G. R. Stengl, Experimental Stress Analysis of the Attachment Region of Hemispherical Shells with Attached Nozzles, Part 3d, Nonradial Nozzle at 22 1/2 Degrees, 2.625 O.D. - 2.125 I.D., 4.00 in. Penetration, Report ME-7-70-2, University of Tennessee (June 1970).
8. R. L. Maxwell, "Experimental Stress Analysis of the Attachment Region of Hemispherical Shells with Single Attached Nozzles," Paper No. 71-PVP-41, American Society of Mechanical Engineers, presented at the Pressure Vessels and Piping Conference, San Francisco, Calif., May 10-12, 1971.
9. R. L. Maxwell, R. W. Holland, and G. R. Stengl, Collapse Test of a Thin-Walled Cylinder to Cylinder Model, University of Tennessee report scheduled for publication in FY 1973.

Auburn University - II

Principal Investigator: W. A. Shaw

Objective

Work at Auburn University is being carried out to develop analytical methods for calculating stresses in the juncture region of spherical shells with single radial and nonradial nozzle attachments. Formulations are developed for analyzing internal pressure loadings of spheres with flush nozzle or with inwardly protruding nozzle attachments.

Description of Models

This is a theoretical study of idealized models of radial and non-radial nozzles attached to spherical shells, with angles of attachment (Ω) ranging from 0 to 25° . In addition, comparisons are made between calculated and experimental results from the University of Tennessee 22 $1/2^\circ$ nonradial nozzle, model TS 802-221.

Scope

In the past, analyses of this type have been limited to small angles of obliquity. This study involves the modification of an existing method* by using an exact description of the nozzle-shell intersection to permit the analysis of nozzles having greater angles of obliquity. Separate formulations are developed for analyzing flush or nonprotruding nozzles and for inwardly protruding nozzles having angles of obliquity of approximately 20° or less. This work is being continued at ORNL (see description of ORNL activities); eventually the formulations are to be extended or modified to include angles of obliquity of 45° or less.

Accomplishments

The first analytical method developed under this subcontract was based on the extension of an existing analytical method, which in turn was based on shallow-shell theory. The method was modified by using an exact description for the nozzle-to-shell intersection rather than the approximate description used previously. This permitted the analysis to be used for larger angles of obliquity. Formulations were then developed for the analysis of both inwardly protruding and nonprotruding nozzles when the shell and nozzle are loaded by internal pressure. Computer programs have been written for analyzing both types of nozzles, and comparisons were made between the theoretical calculations and experimental results from the 22 $1/2^\circ$ nonradial nozzle model TS 802-221, which was tested at the University of Tennessee.

*D. E. Johnson, Stresses Due to Forces on a Nonradial Nozzle in a Spherical Shell, Ph.D. dissertation, Cornell University, June 1963.

Work Planned

The development work scheduled at Auburn University was completed in 1970 (FY 1970). Analytical method development is being continued at ORNL, where modifications have been incorporated to calculate the stresses associated with external loads applied to the nozzle. These include axial forces and bending moments. In addition, the associated computer program is being modified for application to nonradial nozzles with angles of obliquity up to 45° . This work will continue through FY 1973.

Project Reports

1. C. F. Ling and C. H. Chen, Annotated Bibliography on Thin Shells, Technical Report ME-UC2889-1, Auburn University (November 1968).
2. J. C. M. Yu and C. H. Chen, Stresses in the Vicinity of a Nozzle Nonradially Attached to a Spherical Pressure Vessel, Technical Report ME-UC2889-2, Auburn University (April 1969).
3. J. C. M. Yu, C. H. Chen, and W. A. Shaw, Stresses in the Vicinity of a Nozzle Nonradially Attached to a Spherical Pressure Vessel, Technical Report ME-UC2889-3, Auburn University (August 1970).
4. J. C. M. Yu, C. H. Chen, and W. A. Shaw, Stresses in the Vicinity of a Nozzle Non-Radially Attached to and Penetrated into a Spherical Pressure Vessel, Technical Report ME-UC2889-4, Auburn University (October 1970).
5. J. C. M. Yu, C. H. Chen, and W. A. Shaw, "Stress Distribution of a Cylindrical Shell Nonradially Attached to a Spherical Pressure Vessel," Paper No. 71-PVP-42, ASME, presented at the Pressure Vessels and Piping Conference, San Francisco, Calif., May 10-12, 1971.

Westinghouse Research Laboratories

Principal Investigator: M. M. Leven

Objective

Cylindrical and spherical vessels having radial and nonradial nozzles and holes are subjected to photoelastic stress analyses. The results from these tests, together with results of earlier PVRC-sponsored studies, are used as input for developing design code rules and for verifying methods of analysis.

Description of Models

Table 6 lists the radial and nonradial nozzles and holes studied. Included are unreinforced and reinforced nozzles, with some having internal protrusions. The nozzles are divided among three spherical pressure vessels and five cylindrical pressure vessels having hemispherical end closures. The vessels also contain the five holes listed in Table 6. Individual and closely spaced pairs of nozzles are attached to both thin- and thick-walled vessels for comparison.

Scope

The eight machined epoxy models which make up this study are each tested under internal pressure loading, and the photoelastic method of "stress freezing" and slicing is used to determine the stress distributions in the vicinity of each nozzle and hole. The vessels are subjected to a constant internal pressure as the temperature is elevated to a predetermined critical value and subsequently returned slowly to room temperature. The pressure is then removed with the strains remaining "frozen" into the model, and the specimens are sectioned and individual slices analyzed for stresses using polarized light.

Accomplishments

All of the planned tests have been completed, and final project reports have been published. The results for all nozzles and holes are reported individually, and comparisons are made.

The effect of different fabrication techniques on photoelastic stress analysis results was investigated using cylindrical model 1 ($D_i/T = 99.1$, $d_i/D_i = 0.129$, and $s/S = 0.93$) which contained a machined nozzle, WC-2AQ1, a cast nozzle, WC-2AQ2, and a cemented nozzle, WC-2AQ3. The results are given in report (2).

A series of 45° oblique nozzles was studied to compliment the results from PVRC-sponsored studies of spherical shells with oblique holes. Three flush-type nozzles, WN-16B5, WN-16B6, and WS-8H; three nozzles with internal protrusions, WN-16B5B, WN-8B1, and WS-8B2; one interior nozzle, WS-16B5R; and one small radial opening, WS-16, were distributed among three

Table 6. Westinghouse Research Laboratories - nozzle and opening photoelastic tests

Model No.	Nozzle designation	Shell	D_i/T^a	d_i/D_i	s/S	Angle (deg)		Fillet radius ratios ^a		Description
						α , hillside	γ , lateral	r_i/T	R_o/T	
1	WC-2AQ1	Cylinder	99.1	0.129	0.93	0.0	0.0	0.19	0.50	Machined nozzle
1	WC-2AQ2	Cylinder	99.1	0.129	0.93	0.0	0.0	0.19	0.50	Cast nozzle
1	WC-2AQ3	Cylinder	99.1	0.129	0.93	0.0	0.0	0.19	0.50	Straight nozzle, cemented in
5	WC-2AY1	Cylinder	59.4	0.098	0.467	0.0	0.0			Radial nozzle
				0.115	0.187	0.0	0.0	1.30	0.58	Thermal sleeve } combination
5	WC-2AY	Cylinder	59.4	0.115	0.488	0.0	0.0	0.21	0.60	Conventional nozzle to be compared with WC-2AY1
7	WC-12B	Cylinder	12.2	0.022	0.0	0.0	45.0			Lateral hole sealed by disk at midplane
6	WC-12B1	Cylinder	12.2	0.129	1.02	0.0	45.0		0.33	Lateral nozzle
6	WC-12B2	Cylinder	12.2	0.129	0.21	0.0	45.0		0.33	Lateral nozzle
6	WC-12B3	Cylinder	12.2	0.129	0.21	0.0	45.0		0.33	Lateral nozzle with acute inside corner removed
6	WC-12C	Cylinder	12.2	0.020	0.0	45.0	0.0			Hillside hole with thin plate seal at midsurface
6	WC-12C1	Cylinder	12.2	0.129	1.01	60.58	0.0		0.32	Hillside nozzle
7	WC-12C2	Cylinder	12.2	0.022	0.0	78.3	0.0			Hillside hole with thin plate seal at midsurface
7	WC-12C3	Cylinder	12.2	0.067	0.99	60.0	0.0		0.36	Hillside nozzle
7	WC-12D	Cylinder	12.2	0.129	1.0	0.0	0.0	0.24	0.51	Single outside reinforced nozzle
7	WC-12DD	Cylinder	12.2	0.129	1.0	0.0	0.0	0.24	0.51	Two closely spaced outside reinforced nozzles
7	WC-12E	Cylinder	12.2	0.129	1.0	0.0	0.0	0.53	0.55	Single inside reinforced nozzle
8	WC-100D	Cylinder	101.7	0.110	1.0	0.0	0.0	0.27	1.15	Single outside reinforced nozzle
8	WC-100DD	Cylinder	101.7	0.110	1.0	0.0	0.0	0.27	1.15	Two closely spaced outside reinforced nozzles
8	WC-100E	Cylinder	101.7	0.110	1.0	0.0	0.0	1.16	1.17	Single inside reinforced nozzle
8	WC-100C1	Cylinder	101.7	0.110	1.0	60.0	0.0	0.25	1.11	Unreinforced hillside nozzle
5	WC-59B1	Cylinder	59.5	0.115	0.50	0.0	45.0		0.52	Lateral nozzle
4	WS-8H	Sphere	16.5	0.129	0.325	45.0	0.0		0.41	Flush type nozzle
4	WS-8B2	Sphere	16.5	0.129	0.45	45.0	0.0		0.39	Inward protruding nozzle
4	WS-16B5R	Sphere	16.5	0.060	-0.655	45.0	0.0	0.32		Interior flush type nozzle
2	WS-16	Sphere	16.5	0.015	0.0	0.0	0.0			Radial hole with membrane closure
5	WS-63B	Sphere	63.4	0.008	0.0	45.0	0.0			Small hole with thin plate seal at midsurface
5	WS-63B1	Sphere	63.4	0.04	0.92	45.0	0.0		0.46	Flush nozzle
5	WS-63B2	Sphere	63.4	0.04	0.10	45.0	0.0		0.46	Flush nozzle
3	WN-8B1	Sphere	16.5	0.129	0.67	45.0	0.0		0.32	Inward protruding nozzle
2	WN-16B5	Sphere	16.5	0.062	0.68	45.0	0.0		0.32	Flush-type machined nozzle
2	WN-16B5A	Sphere	16.5	0.062	0.68	45.0	0.0		0.32	Flush-type nozzle, cemented in
3	WN-16B6	Sphere	16.5	0.031	0.69	45.0	0.0		0.18	Flush-type nozzle
2	WN-16B5B	Sphere	16.5	0.061	0.68	45.0	0.0		0.32	Inward protruding nozzle
3	WN-16B5C	Sphere	16.5	0.061	0.67	45.0	0.0			Flush type, cemented to vessel at inner portion of nozzle
6	WUW-2	Sphere	18.6	0.130	0.63	60.58	0.0		0.36	Flush nozzle

^a D_i = inside diameter of vessel; T = thickness of vessel; d_i = inside diameter of nozzle; s = nominal stress in nozzle;
S = nominal stress in vessel; α = angle of inclination of hillside opening; γ = angle of inclination of lateral opening;
 r_i = inside fillet radius; R_o = outside fillet radius.

spherical models 2, 3, and 4 ($D_i/T = 16.5$). The results are presented in report (3) and the results for the corresponding oblique holes are given in report (1).

Cylindrical photoelastic models 5, 6, 7, and 8 were used to study reinforced and closely spaced nozzles. Included in cylindrical model 5 are five nozzles and one hole. Nozzle WC-2AY1 has balanced reinforcement and a thermal sleeve; its comparison conventional unreinforced nozzle is WC-2AY. Both of these nozzles were attached to the cylindrical portion of the vessel. The test results for these two nozzles are given in report (4). Nozzle WC-59B1 is a lateral connection having an internal diameter $d_i = 1.727$ in. and a thickness $t = 0.060$ in., as compared with $d_i = 1.719$ in. and $t = 0.060$ in. for WC-2AY. The test results for WC-59B1 are given in report (6).

The spherical end caps of cylindrical model 5 contained a small hole, WS-63B, which was gasketed at its midsurface, and nozzles WS-63B1 and WS-63B2. Nozzle WS-63B1 was an unreinforced thin-walled nozzle, and WS-63B2 was a reinforced thick-walled nozzle. The experimental stress analyses of the hole and two nozzles attached to the end caps are given in report (6).

Cylindrical model 6 contained five nozzles and one hillside hole. The hillside hole WC-12C was in the cylindrical portion of the shell, and, for comparison purposes the model had an attached unreinforced hillside nozzle WC-12C1. Another set consisted of three lateral nozzle-to-cylindrical shell attachments; one was an unreinforced nozzle (WC-12B1) and two (WC-12B2 and WC-12B3) were reinforced with thickened walls. The reinforced nozzles were identical, except that the acute inside corner was removed in the case of WC-12B3. The results for these four nozzles and one hole are included in report (7).

The fifth nozzle in cylindrical model 6 (WUW-2) was a copy of a similar nozzle (UW-2) tested at the University of Waterloo, except that the UW-2 nozzle had generously rounded inside corners while those of WUW-2 were sharp. The results for this fifth nozzle are given in report (5).

Cylindrical model 7 had an inside diameter-to-thickness ratio (D_i/T) of 12.2; cylindrical model 8 had a D_i/T ratio of 101.7. Each of the two cylindrical vessels contained closely spaced pairs of reinforced nozzles

(WC-12DD and WC-100DD respectively) mounted along the longitudinal axis. For comparison purposes, single reinforced nozzles (WC-12D and WC-100D respectively) identical to each closely spaced nozzle, were also attached to the cylindrical vessels. In addition, nozzles WC-12E and WC-100E, having internal protrusions and reinforcement internal to the vessel but with the same basic dimensions as the three reinforced nozzles, were attached to each vessel. The two vessels also contained unreinforced hillside nozzles WC-12C3 and WC-100C1 respectively. The results for the closely spaced nozzles and companion single nozzles are given in report (8). Two additional openings included in model 7 were a lateral hole (WC-12B) and a hillside hole (WC-12C2). The bore of the latter was tangential to the inner surface of the shell.

Work Planned

The studies under this project were completed in 1971 (FY 1971), and no additional work is currently planned.

Project Reports

1. M. M. Leven, Determination of Stresses at Non-Radial Openings in Spherical Pressure Vessels, Report 66-9D7-520-R1, Westinghouse Research Laboratories (March 1966).
2. M. M. Leven, Photoelastic Determination of Stresses at an Opening in a Thin-Walled Cylindrical Pressure Vessel, Report 67-9D7-PHOTO-R1, Westinghouse Research Laboratories (Aug. 24, 1967).
3. M. M. Leven, Photoelastic Determination of Stresses at Oblique Openings in Spherical Pressure Vessels, Report 67-9D7-PHOTO-R2, Westinghouse Research Laboratories (Nov. 22, 1967).
4. M. M. Leven, Photoelastic Determination of Stresses in a Reinforced Steam Charging Connection with a Thermal Sleeve, Research Report 69-9D7-PHOTO-R1, Westinghouse Research Laboratories (Jan. 14, 1969).
5. M. M. Leven, Summary of Oblique Openings in Spherical Shells, Research Report 69-9D7-PHOTO-R2, Westinghouse Research Laboratories (Mar. 20, 1969).
6. M. M. Leven, Photoelastic Determination of the Stresses at Oblique Openings in Cylindrical Pressure Vessels, Research Report 69-9E7-PHOTO-R1, Westinghouse Research Laboratories (Sept. 10, 1969).

7. M. M. Leven, Photoelastic Determination of the Stresses at Oblique Openings in Spherical Pressure Vessels, Research Report 69-9E7-PHOTO-R2, Westinghouse Research Laboratories (Oct. 29, 1969).
8. M. M. Leven, Stress Distribution at Two Closely-Spaced Reinforced Openings in a Pressurized Cylinder, Research Report 71-9E7-PHOTO-R1, Westinghouse Research Laboratories (Apr. 9, 1971).

University of Waterloo - I

Principal Investigator: N. C. Lind

Objective

This investigation includes both elastic behavior and plastic limit studies. The elastic behavior of nozzle-to-shell intersections is studied experimentally, and a simplified method of elastic stress analysis is developed. In addition, tees and nozzle-to-spherical shell attachments are subjected to limit load testing. Both upper- and lower-bound equations are developed for the spherical shells having radially attached nozzles.

Description of Models

The models tested under this program are described in Table 7. Elastic tests are conducted on three nonradial nozzle models, one strain-gaged steel model and two photoelastic models. In addition, two carbon steel commercial tees, a $10 \times 10 \times 10$ in. sched-40 straight tee and a $10 \times 10 \times 5$ in. sched-40 reducing tee, are subjected to plastic collapse testing as were the five nozzle-to-spherical shell attachment models listed in Table 7. Of the latter models, model 2 was tested twice. Following the initial test the model was reformed by bending to its approximate original shape, and a second test was conducted.

Scope

This investigation consists of three separate studies. Elastic stress distributions in the juncture regions of laterals and a nonradial nozzle-to-spherical shell attachment are studied. A simplified method is being developed for determining elastic stresses at the juncture which

Table 7. University of Waterloo models

Model designation	Description	d_m (in.)	D_m (in.)	t (in.)	T	d_m/D_m	D_m/T	s/s^a
<u>Elastic test models</u>								
UW-1	45° lateral (photo-elastic model)	4.625	9.382	0.250	0.763	0.493	12.30	1.08
UW-2	60.97° nonradial nozzle-to-sphere attachment (photoelastic model)	1.415	10.273	0.254	0.546	0.138	18.82	0.629
UW-1S	45° lateral (steel model)	4.688	9.375	0.375	0.750	0.500	12.50	1.00
<u>Plastic collapse test, commercial tees</u>								
UW-3	10 × 10 × 5-in. sched-40 carbon steel reducing tee							
UW-4	10 × 10 × 10-in. sched-40 carbon steel straight tee							
<u>Plastic collapse test, nozzle-to-spherical shell models</u>								
1	Internal pressure plus moment loading applied to nozzle	2.380	12.180	0.5	0.155	0.195	78.58	0.121
2a	Internal pressure plus moment loading applied to nozzle	2.400	12.084	0.5	0.125	0.199	96.67	0.100
2b	Same model retasted with internal pressure only							
3	Internal pressure plus moment loading applied to nozzle	2.387	12.392	0.5	0.168	0.193	73.76	0.130
4	Internal pressure plus axial force on nozzle	2.400	11.886	0.5	0.219	0.202	58.85	0.177
5	Internal pressure plus skewing force on nozzle	2.400	11.886	0.5	0.230	0.202	51.68	0.186

^aFor pressure.

result from internal pressure loadings. In another study, tests are conducted to determine plastic limit pressures for two commercial tees.

Theoretical and experimental limit load studies of nozzles attached radially to spherical shells are also conducted, in which a series of five models is subjected to combinations of internal pressure and externally applied nozzle loadings. The resulting data are used to evaluate corresponding upper- and lower-bound equations for spherical shells with rigid radially attached nozzles.

Accomplishments

A simplified analysis, called "the area method," was developed for determining maximum elastic stresses at pressurized nozzle-to-spherical shell junctions. A similar analysis was developed for pressurized nozzle-to-cylindrical shell attachments. The two nonradial nozzle photoelastic models (models UW-1 and UW-2) were tested under internal pressure loadings, and the results were reported (2). The steel, 45° nonradial model (model UW-1S) was used to study stresses and deformations resulting from force loadings applied to the nozzle. The results were reported in report (8); however, part III of this report was not published.

The two tee connections listed in Table 7 were tested under internal pressure loading to determine the limit pressures of these commercial carbon steel fittings (models UW-3 and UW-4). A simplified method was developed for determining elastic stresses at the crotch of cylinder-to-cylinder connections under internal pressure loading when

$$(\beta \rho_0) = \frac{d}{4} [3(1 - \nu^2)]^{1/4} (RT)^{-1/2}$$

is large [see report (9)]. In Lind's work, β is substituted for the $(\beta \rho_0)$ term.

Upper- and lower-bound equations were derived for spherical shells with radially attached nozzles when subjected to combined loadings of internal pressure and small moments and shear forces acting on the nozzles. The experimental study of five nozzle-to-spherical shell attachments was done in support of the analytical work. The models were subjected to the

combinations of internal pressure and small moment and shear loadings listed in Table 7, and a final report has been published (10).

Work Planned

The planned investigations have been completed and the final reports submitted to PVRC. The last report was processed in 1970 (FY 1969).

Project Reports

1. N. C. Lind, "A Rapid Method to Estimate the Elastic Stress Concentration of a Nozzle in a Spherical Pressure Vessel," Nucl. Struct. Eng. 2, 159-68 (1965).
2. C. E. Taylor and N. C. Lind, Photoelastic Study of the Stresses near Openings in Pressure Vessels, Welding Research Council Bulletin 113, April 1966.
3. S. Palusamy, Plastic Analysis of Pressurized Intersecting Shells under a Small External Force Disturbance, Master of Applied Science thesis, University of Waterloo, September 1966.
4. S. Palusamy, "Limit Analysis of Intersecting Shells under Small External Force Disturbance," February 1967 (undocumented).
5. N. C. Lind and S. Palusamy, "Experimental Investigation of Intersecting Shells under a Small External Force Disturbance," September 1967 (undocumented).
6. N. C. Lind, "Approximate Stress-Concentration Analysis for Pressurized Branch Pipe Connections," ASME Paper 67-WA/PVP-7, November 1967.
7. N. C. Lind, A. N. Sherbourne, F. Ellyin, and J. Dainora, Plastic Tests of Two Branch Pipe Connections, University of Waterloo (September 1968).
8. P. K. Fung and N. C. Lind, Experimental Stress Analysis of a 45° Lateral Branch Pipe Connection Subjected to External Loadings, Parts I, II, and III, University of Waterloo (September 1969).
9. N. C. Lind, "An Elastic-Shell Analysis of the Stress Concentration of a Pressurized Tee Branch-Pipe Connection," Pressure Vessel Technology, Part I, Design and Analysis, pp. 269-75, ASME, 1969.
10. S. Palusamy and N. C. Lind, "Limit Analysis of Rigid Radial Nozzles in Spherical Pressure Vessels under Combined Loading," report submitted to Subcommittee on Reinforced Openings and External Loadings of the PVRC Design Division, University of Waterloo, December 1969.

Additional Publications

1. N. C. Lind and S. Palusamy, Experiments on Plastic Limit Behavior of Shell-Nozzle Junctions Subjected to Nonsymmetrical Loading, Report No. 47, Solid Mechanics Division, University of Waterloo (June 1970); (also ASME Paper 71-PVP-45).
2. S. Palusamy and N. C. Lind, Optimization Limit Analysis of Spherical Shells under Non-Symmetrical Loadings, Reprint Study No. 5, Computer-Aided Engineering, University of Waterloo (undated).
3. S. Palusamy, "Limit Pressure of Spherical Shells Subjected to External Axial Force," Nucl. Eng. Design 16, 13-23 (1971).
4. S. Palusamy and N. C. Lind, "A Consistent Theory for Spherical Shells in Equilibrium," Nucl. Eng. Design 21, 350-57 (1971).
5. S. Palusamy and N. C. Lind, "Limit Analysis of Nonsymmetrically Loaded Spherical Shells," J. Appl. Mech. 39, 422-30, ASME (June 1972).
6. S. Palusamy, "Influence of External Loads on Pressure Carrying Capacity of Outlet Connections," Paper No. 72-PVP-8, American Society of Mechanical Engineers, to be published in J. Eng. Ind.

University of Waterloo - II

Principal Investigator: J. Schroeder

Objective

Computerized methods of analysis are developed for the determination of upper bounds to limit loadings of tees and laterals, and a series of experimental models are tested to provide data for evaluating the resulting analytical methods.

Description of Models

The analytical studies include tees and laterals having branch-to-run ratios (d/D) from zero to 1.0, diameter-to-thickness ratios (D/T) greater than 20, elastic branch-to-run hoop stress ratios (s/S) of 0.25 to 3.0, and branch-to-run angles between 30 and 90°. Both idealized configurations and those having fillet reinforcement at the nozzle-shell junction are considered.

Represented in the experimental study are tees and laterals having d/D ratios of 0.5 to 1.0, D/T ratios of 14.6 to 34.5, and branch-to-pipe

hoop stress ratios (s/S) of 0.55 to 1.0. In addition, a limited number of straight pipe sections are tested to provide required supplementary limit load data.

Scope

Equations are derived and the associated computer programs developed to calculate limit loads for laterals and tees under either internal pressure loading or loadings applied externally to the nozzle; the latter includes axial thrust, shear, bending moments, and torsional moments. In addition, the computational methods will be capable of analyzing various combinations of these loadings.

A companion series of experimental studies is being conducted along with the analysis development work. Included are 15 tees, ten 45° laterals, and four straight-pipe sections. The dimensions of these models, together with the types of loading employed, are given in Table 8. The applied loadings include internal pressure (P), in-plane and out-of-plane couples applied to the branch (designated as C_i and C_o respectively), and moment loadings (C) applied to the pipe sections. Three of the models will be tested under combined loadings of internal pressure and either an in-plane or out-of-plane couple. Yield strengths will be obtained for each model using uniaxial test specimens obtained from undeformed ends of the model and/or annealed specimens machined from the plastically deformed zones.

Accomplishments

Two separate formulations and methods for determining upper-bound limit pressures have been developed to cover the full d/D range. This division is necessary because for laterals having d/D ratios approaching unity, the plastic region has a complex geometry, and high strain concentrations are developed at the inside acute corner of the junction. One formulation (2) is applicable to d/D ratios of from 0 to 0.7, and the other (3) is applicable to values of d/D ranging from 0.7 to 1.0.

With the exception of model T_{11} , all models listed in Table 8 have been tested, and preliminary results have been made available. A final report on all tests is in the final stages of preparation.

Table 8. University of Waterloo plastic limit tests of cylinder-to-cylinder connections

P = internal pressure, C_i = in-plane couple on branch, C_o = out-of-plane couple on branch, C = couple on straight pipe, ϕ_A = external fillet radius on crotch for angles $\geq 90^\circ$, ϕ_o = external fillet radius on crotch for angles $\leq 90^\circ$

Model No.	D (in.)	d/D	D/T	s/S	ϕ_A (in.)	ϕ_o (in.)	Loading	Pipe end support	Date of test
<u>Machined 45° laterals</u>									
Y ₁	3.45	1.00	34.5	1.00	1.00	0.25	P	Single	Mar. 1968
Y ₂	3.48	1.00	26.8	1.00	1.00	0.25	P	Single	May 1970
Y ₃	3.49	0.75	25.0	1.00	1.00	0.25	C_i	Double	Aug. 1971
Y ₄	3.47	0.63	29.0	0.94	1.00	0.25	P	Double	Apr. 1969
Y ₁₀	3.48	1.00	26.8	1.00	1.00	0.25	P	Single	
<u>Welded 45° laterals</u>									
Y ₅	3.20	1.00	14.6	1.00			P	Single	Oct. 1969
Y ₆	4.30	1.00	17.0	1.00			P	Single	Aug. 1969
Y ₇	4.30	0.77	17.2	0.80			P	Single	Oct. 1970
Y ₈	4.30	1.00	17.7	1.00			P	Single	Oct. 1970
Y ₉	3.50	0.63	22.0	1.00	1.00	0.25	C_o	Double	Apr. 1971
<u>Machined tees</u>									
T ₁	3.45	1.00	32.8	1.00	0.50	0.50	P	Single	July 1968
T ₂	3.45	0.63	34.5	0.90	0.50	0.50	P	Single	Oct. 1969
T ₃	3.64	0.83	26.0	1.00	0.50	0.50	P	Single	Apr. 1969
T ₄	3.49	0.50	25.0	1.00	0.25	0.25	C_o	Double	Dec. 1971
T ₅	3.49	0.75	25.0	1.00	0.50	0.50	C_i	Double	June 1971
T ₆	3.49	1.00	25.0	1.00	0.25	0.25	C_o	Double	Jan. 1972
T ₇	3.49	1.00	25.0	1.00	0.50	0.50	P	Single	July 1971
T ₈	3.49	0.50	25.0	1.00	0.25	0.25	C_i	Double	Jan. 1972
T ₉	3.49	1.00	25.0	1.00	0.50	0.50	C_i	Double	Nov. 1971
T ₁₀	3.45	0.70	34.5	0.55	0.38	0.38	C_o	Double	Aug. 1971
T ₁₁	3.49	0.75	25.0	1.00	0.50	0.50	P, C_i	Single	
T ₁₂	3.48	1.00	26.8	1.00	0.50	0.50	P, C_i	Single	
T ₁₃	3.45	1.00	34.5	0.55	0.50	0.50	P, C_o	Single	
<u>Straight pipes</u>									
P ₁	3.15		21.0				C	Double	
P ₂	3.10		31.0				P	Single	
P ₃	3.60		41.0				P, C		
P ₄	3.60		51.0				C		

Analytical methods and associated computer programs are also being developed to calculate upper bounds to in-plane and out-of-plane limit couples for d/D ratios up to 0.9. Thus far two computer programs have been completed and forwarded to ORNL, where they will be maintained and used for conducting parameter studies. Both programs are for calculating upper bounds for tees and laterals with diameter ratios of 0.1 to 0.7. One program is for internal pressure loadings only, and the other is for in-plane couples as well as combinations of in-plane couples and internal pressure.

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The last remaining test will be completed, and a report containing all experimental results will be written. A third computer program for out-of-plane couples as well as combinations of out-of-plane couples and internal pressure loadings will be completed.

Project Reports

1. J. Schroeder and P. Rangarajan, "Upper Bounds to Limit Pressures of Branch-Pipe Tee Connections," Pressure Vessel Technology, Part I, Design and Analysis, pp. 277-91, ASME, 1969.
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3. J. Schroeder, "Upper Bounds to Limit Pressures of Branch-Pipe Lateral Connections, Part II: Bounds and Reliability for Branch/Pipe Diameter Ratio Larger than 0.7," Paper No. 71-FVP-44, ASME, May 1971.

University of Sherbrooke

Principal Investigator: F. Ellyin

Objective

This investigation involves both a study of elastic stress distributions in the vicinity of single skewed holes in flat plates and the development of lower bounds to limit loads for shells having attached single nozzles.

Description of Models

The two basic types of models being investigated are perforated flat plates and single nozzle-to-shell attachments. Table 9 lists the 30 models that comprise the flat-plate experimental investigation. The first ten of these plates are used to conduct a basic study of elastic stress concentrations. The variables of interest in this study are the diameter and both direction and degree of skewness of the holes; the plate thickness is essentially constant at slightly under 1.0 in.

The next set of 14 specimens listed in Table 9 constitute the elastic study of hole edge shapes. The sharp acute corners of nine of these plates are modified by flattening one corner (indicated in the table by k , the length of the flattened portion normal to the face of the plate) and by rounding the opposite corner (indicated by r , the radius of the rounded acute corner).

The final series of six plates shown in Table 9 make up the elastic-plastic strain study specimens. The primary variables considered in this study are hole radius and degree of skewness; again the plate thickness is essentially constant.

The specimens tested under the investigation of elastic-plastic behavior of nozzle-to-spherical shell attachments under internal pressure loadings are listed in Table 10. The first seven models consist of hemispherical shells with a central cutout to which a right cylindrical shell is attached by welding.

The last four models in the table, those having designation numbers ending with a C, are fabricated from the correspondingly numbered E series model. A conical transition section is included in these models between the nozzle and shell, and each model is instrumented with electrical resistance strain gages and mechanical dial gages.

In the most recent study of elastic-plastic behavior of nozzle-to-shell attachments, three models composed of single nozzles attached normally to cylindrical shells will be tested. These are idealized models, which will each be machined in one piece from a steel block and tested under combinations of internal pressure and either in-plane or out-of-plane bending moment loadings. The resulting data will be used to evaluate

Table 9. University of Sherbrooke flat-plate models

Plate No.	Plate			Hole				
	Thickness (in.)	Width (in.)	Length (in.)	Diameter (in.)	Angle of skewness (deg)	Direction of skewness	r^a (in.)	k^b (in.)
<u>Elastic stress study</u>								
1	0.960	12.0	32.0	2.50	0			
2	0.966	12.0	32.0	2.50	15	Longitudinal		
3	0.951	12.0	32.2	2.50	15	Transversal		
4	0.957	12.0	36.0	2.50	30	Longitudinal		
5	0.935	12.0	36.0	2.50	30	Transversal		
6	0.951	12.0	36.0	2.50	45	Transversal		
7	0.944	12.0	35.9	2.50	45	Longitudinal		
8	0.951	12.0	32.2	3.75	45	Transversal		
9	0.957	12.0	36.0	3.75	30	Transversal		
10	0.951	12.0	36.0	3.75	45	Transversal		
<u>Elastic stress study of corner shapes</u>								
1	0.976	12.0	36.0	2.50	30	Longitudinal		
2	0.972	12.0	36.0	2.50	45	Longitudinal		
3	0.957	12.0	36.0	2.50	60	Longitudinal		
4	0.966	12.0	36.0	1.50	45	Longitudinal		
5	0.979	12.0	36.0	1.50	60	Longitudinal		
1a	0.976	12.0	36.0	2.50	30	Longitudinal	0.187	0.137
2a	0.972	12.0	36.0	2.50	45	Longitudinal	0.187	0.264
3a	0.957	12.0	36.0	2.50	60	Longitudinal	0.187	0.511
6a	0.966	12.0	36.0	2.50	45	Longitudinal	0.321	0.454
1b	0.976	12.0	36.0	2.50	30	Longitudinal	0.187	0.137
2b	0.972	12.0	36.0	2.50	45	Longitudinal	0.187	0.264
3b	0.957	12.0	36.0	2.50	60	Longitudinal	0.187	0.511
7b	0.979	12.0	36.0	2.50	45	Longitudinal	0.321	0.454
3c	0.957	12.0	36.0	2.874	60	Longitudinal	0.187	0.511
<u>Elastoplastic strain distribution study</u>								
0	0.982	11.880	36.0	2.5	0	Longitudinal		
1	0.976	11.904	36.0	2.5	30	Longitudinal		
2	0.972	11.965	36.0	2.5	45	Longitudinal		
3	0.957	11.925	36.0	2.5	60	Longitudinal		
4	0.966	11.894	36.0	1.5	45	Longitudinal		
5	0.979	11.912	36.0	1.5	60	Longitudinal		

^a_r = the radius of the rounded acute corner of hole edge.

^b_k = length of the flattened portion of the acute corner normal to the face of the plate.

Table 10. University of Sherbrooke steel
spherical shell models

Model No.	Nozzle		Vessel		Conical pad	
	Diameter (in.)	Thickness (in.)	Diameter (in.)	Thickness (in.)	Length (in.)	Angle (deg)
E1	5.863	0.134	19.644	0.220		
E2	5.865	0.133	19.669	0.221		
E3	6.813	0.193	19.698	0.222		
E4	4.439	0.064	19.815	0.122		
E5	3.912	0.098	19.788	0.120		
E6	3.383	0.121	14.738	0.222		
E7	2.755	0.124	14.722	0.226		
E2C	5.868	0.133	19.747	0.216	2.75	30.77
E3C	6.811	0.193	19.702	0.218	3.25	36.15
E4C	4.388	0.064	19.830	0.122	5.00	31.12
E5C	3.916	0.098	19.821	0.120	4.20	27.50

lower bounds to limit loads which are calculated using the analysis methods developed under this project.

Scope

The investigation of stresses near skewed holes in flat plates involves both theoretical and experimental efforts. Initially a basic study is made of elastic strains and stresses in the vicinity of skewed holes. This is followed by a study of the relationship of sharpness of acute corners along the edge of skewed holes in flat plates. In a third study, elastic-plastic strain distributions are investigated for the skewed hole configuration.

Strains are measured both around the hole and through the depth while the plate is loaded in uniaxial tension. These studies encompass hole diameter-to-plate thickness ratios (d/T) ranging from 1.53 to 3.94 and angles of inclination of 0, 15, 30, 45, and 60 deg.

The investigation of plastic collapse behavior of nozzle-to-spherical shell attachments consists of a combination of experimental studies and theoretical limit analysis development for determining plastic collapse pressures. The theoretical work is based on rigid-perfectly plastic behavior. In addition, four models having conical transitions between the nozzle and spherical shell are tested to determine the limit pressure of this configuration.

The development of analytical methods for determining both upper and lower bounds to limit pressures for cylindrical shells with single radial nozzles was initiated; however, since the PVRC has limited its support of plastic collapse load studies and, in the case of this project, to the development of lower bounds, the upper-bound development work has not been continued at the University of Sherbrooke. A lower bound analysis is to be developed for various types of individual loadings of tees consisting of internal pressure, three types of moment loadings (in-plane, out-of-plane, and torsion), and force loadings (axial and normal forces) as well as possible combinations. The analysis will be in the form of a single computer program which will be used to conduct parameter studies.

Accomplishments

The study of stresses near skewed holes in flat plates has been completed. In the study of elastic stresses, stress concentrations were measured along the edge faces or surfaces of the hole for various angles of skewness. The skewed holes were oriented either longitudinally or transversely to the direction of loading. Holes having diameters of 2.5 and 3.75 in. were studied.

In a subsequent study, 14 plate specimens were tested to determine the effect of edge sharpness on stress concentrations around skewed holes. The sharpness of the plate edges was reduced either by rounding the acute corner to a circular profile of radius r or by making a cylindrical cut normal to the surface of the plate at the acute corner. Included in this study were holes having radii of 1.5, 2.5, and 2.874 in.

The elastic-plastic behavior study utilized six plate specimens having hole diameters of 1.5 and 2.5 in. and angles of inclination of 0, 30, 45, and 60 deg. The elastic-plastic response of the plate to uniaxial loading

was measured using bonded electrical resistance strain gages located around the hole on both the face and on the edge of the plate. The critical values of elastic strain obtained from the tests are used to determine the nominal stress level at which high stress concentrations are relieved by plastic strains.

A theoretical analysis of individual skewed holes in flat plates has been developed in conjunction with the elastic studies, and the analytical results have been compared with corresponding test results.

The testing of four models having conical transitions between the nozzle and spherical shell has been completed. However, the results failed to confirm the proposed theory that the use of a conical transition would increase the limit pressure of a nozzle-to-spherical shell configuration.

In more recent studies of elastic-plastic behavior, preliminary analytical methods for calculating lower and upper bounds to limit pressures of nozzle-to-cylindrical shell attachments were developed. Lower bounds to limit pressures were calculated using the initial formulation and compared with available test data. The comparisons indicated that the values were quite conservative; therefore, an improved formulation was developed to reduce the conservatism. The new development eliminates the need for using simplifying assumptions at the junction of the nozzle and vessel and also incorporates the technique of enforcing yield constraints at selected points on the juncture region (19). Results from this second method have been compared with experimental data provided by the University of Waterloo as well as with other data.

Analytical methods have also been developed for determining lower bounds to both in-plane and out-of-plane limit couples of cylinder-to-cylinder connections; the analyses are applicable to all nozzle-to-cylinder diameter ratios. Parameter studies have been conducted using the out-of-plane limit couple analysis. A computer program, which is capable of calculating limit loads for internal pressure and out-of-plane bending of the nozzle separately, has been made operational on the computer at ORNL.

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The capability of the computer program will be extended to include the calculation of lower bounds for any of three types of moment loadings (in plane, out of plane, and torsion) or for external force loadings. Demonstration analyses will be conducted using the computer program, and the program will be modified as the need becomes apparent.

The computer program will eventually be modified to include the capability of calculating lower bounds for various combinations of external loadings and internal pressure, and a user's manual will be prepared. Parameter studies will be made using selected combinations of loadings.

An initial series of tests of three idealized cylinder-to-cylinder attachment models has been proposed to provide experimental data for evaluating the lower-bound analysis. The models will be subjected to individual loadings of internal pressure, in-plane moment or out-of-plane moment. Loadings to be used for the analytical parameter studies and for any additional experimental models will be selected based on recommendations of the PVRC Subcommittee on Reinforced Openings and External Loadings.

Project Reports

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2. F. Ellyin, N. C. Lind, and A. N. Sherbourne, "Elastic Stress Field in a Plate with a Skew Hole," J. Eng. Mech. Div., ASCE 92(EM1), 1-10 (February 1966).
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Oak Ridge National Laboratory

Principal Investigators: W. L. Greenstreet, R. C. Gwaltney,
and J. P. Callahan

Objective

Work under way at ORNL in addition to program management responsibilities consists of the performance of analytical parameter studies and experimental stress analyses, the derivation and programming of stress analysis methods for the computer, and the maintenance of a central depository for computer programs having application to the study of nozzles. Each computer program included in the depository is made operational on the ORNL computer for use in the various studies.

Description of Models

Parametric studies are conducted on the various model configurations listed in Tables 11 through 16. Included are cylindrical shells having a step change in outside diameter, and nozzle-to-spherical shell attachments having various amounts and types of nozzle reinforcement.

A series of four strain-gaged steel nozzle-to-cylindrical shell models are being studied both experimentally and analytically at ORNL. The major dimensions of the idealized thin-walled models are shown in Fig. 1. Model 1 is instrumented with 966 strain gage elements in the form of three-gage rosettes, and the three remaining models are instrumented with approximately 500 strain gage elements each.

Scope

The parametric studies are conducted using either analytical methods available in the literature and/or the methods developed under this program. The range of model parameters, some of which are indicated in Tables 11 through 16, is selected based on the theoretical limitations of the analysis being used and the needs determined through the code-rule development work at Battelle Memorial Institute (Rodabaugh).

Under the experimental study of steel nozzle-to-cylindrical shell models, each of the four models listed in Fig. 1 is subjected to 13 loadings consisting of internal pressure, moments applied in three orthogonal

Table 11. Model parameters employed in a study of the effect of fillets in cylindrical shells with step changes in outside diameter

Configuration	Model No.	t	T	T/t	ϕ	ϕ/t	a	a/t
I	11	0.5	0.75	1.5	0.025	0.05	2.5	5
	12						5.0	10
	13						10.0	20
	21				0.075	0.15	2.5	5
	22						5.0	10
	23						10.0	20
	31				0.150	0.30	2.5	5
	32						5.0	10
	33						10.0	20
	41				0.225	0.45	2.5	5
	42						5.0	10
	43						2.5	20
II	11	0.5	2.0	4.0	0.075	0.15	2.5	5
	12						5.0	10
	13						10.0	20
	21				0.1125	0.225	2.5	5
	22						5.0	10
	23						10.0	20
	31				0.150	0.30	2.5	5
	32						5.0	10
	33						10.0	20
	41				0.225	0.45	2.5	5
	42						5.0	10
	43						10.0	20
	51				0.300	0.60	2.5	5
	52						5.0	10
	53						10.0	20

t = thickness of the thinner section, in.

T = thickness of the thicker section, in.

ϕ = fillet radius, in.

a = inside radius of the cylindrical shell, in.

Configuration = set of models with the same T/t ratio.

Model No. = single model within a configuration, with different ϕ/t and a/t ratios.

Table 12. Models used in a comparative study of results obtained by experiment, finite-element analysis, and shell analysis for internal pressure loading of nozzle-to-spherical shell attachments

Model No.	D_i/T	d_i/D_i	s/S	ϕ_o/T	$A_i/d_i T$	$A_o/d_i T$	Method ^a
S-2AZ	66.3	0.129	0.994	0.194	0	0.001	Test Shell
S-5AZ	70.3	0.500	1.02	0.785	0	0.005	Test Shell
S-1AB	24.0	0.50	1.00	0.558	0	0.091	Test Shell
WN-10D	24.1	0.201	1.02	1.56	0	0.100	Test Shell
WN-6B	23.9	0.201	1.01	2.91	0.325	0.325	Test Shell
WS-5LO	71.5	0.501	1.02	13.25	0.325	0.325	Test Shell
WN-10B	24.1	0.201	1.02	4.35	0	0.650	Test Shell F.E.
S-24A	24.0	0.200	1.00	0.333	0	0.007	Shell F.E.
S-24D	24.0	0.200	1.00	3.31	0	0.440	Shell F.E.
S-72A	71.9	0.200	1.00	0.402	0	0.003	Shell F.E.
S-72D	71.9	0.200	1.00	8.62	0	1.00	Shell F.E.
S-24F	24.0	0.200	1.00	0.333	0.88	0.007	Shell F.E.
S-72F	71.9	0.200	1.00	0.402	1.00	0.003	Shell F.E.
S-24H	24.0	0.200	1.00	0.333	1.24	0.007	Shell F.E.

^aTest = photoelastic test data, shell = computer program STATIC, and F.E. = finite-element program.

NOTE: D_i = inside diameter of spherical shell; T = wall thickness of spherical shell; d_i = inside diameter of cylindrical nozzle; s = nominal hoop stress in nozzle; S = nominal stress in sphere; ϕ_o = outside fillet radius.

Table 13. Models employed in a parametric study of inside versus outside reinforcement^a

Model No.	D_i/T	d_i/D_i	$A_i/d_i T$	$A_o/d_i T$	ϕ_o/T
S-24/10H1	24	0.10	1.00	0.03	0.50
S-24/10HD			1.00	0.06	0.695
S-24/10H.8			0.80	0.20	1.286
S-24/10H.6			0.60	0.40	1.870
S-24/10H.4			0.40	0.60	2.340
S-24/10H.2			0.20	0.80	2.750
S-24/10B			0.00	1.00	3.130
S-72/10H1	72	0.10	1.00	0.01	0.5
S-72/10HD			1.00	0.06	1.20
S-72/10H.8			0.80	0.20	2.16
S-72/10H.6			0.60	0.40	3.10
S-72/10H.4			0.40	0.60	3.85
S-72/10H.2			0.20	0.80	4.48
S-72/10B			0.00	1.00	5.07
S-24/50H1	24	0.50	1.00	0.001	0.50
S-24/50HD			1.00	0.06	3.47
S-24/50H.8			0.80	0.20	6.41
S-24/50H.6			0.60	0.40	10.02
S-24/50H.4			0.40	0.60	13.30
S-24/50H.2			0.20	0.80	16.43
S-24/50B			0.00	1.00	19.40
S-72/50H1	72	0.50	1.00	<0.001	0.5
S-72/50HD			1.00	0.08	6.00
S-72/50H.8			0.80	0.20	9.60
S-72/50H.6			0.60	0.40	14.40
S-72/50H.4			0.40	0.60	18.45
S-72/50H.2			0.20	0.80	22.10
S-72/50B			0.00	1.00	25.50

^a A_i = inside reinforcement area, A_o = outside reinforcement area, and ϕ_o = outside fillet radius. See Table 12 for definition of all other terms.

Table 14. Summary of models included in study of nozzles in spherical shells with triangular pad reinforcing^a

D_i/T	d_i/D_i	$2A/d_i T$	ϕ_3/T		ϕ_4/T	
			$\theta = 30^\circ$	$\theta = 60^\circ$	$\theta = 30$	$\theta = 60$
10	0.08	0.819*	1.29	1.82	0.333	0.167
	0.16	0.987	1.29		0.333	
	0.32	0.947	1.29		0.605	
	0.50	0.866				
20	0.04	0.305*	1.83	2.58	0.333	0.167
	0.08	0.997	1.83	2.58	0.333	0.167
	0.16	0.987	1.83		0.427	
	0.32	0.947	1.83		0.855	
	0.50	0.866				
40	0.04	0.819*	2.58	3.65	0.333	0.167
	0.08	0.997	2.58	3.65	0.333	0.167
	0.16	0.987	2.58	3.65	0.605	0.262
	0.32	0.947	2.58		1.208	
	0.50	0.866	2.58		1.890	
80	0.02	0.305*	3.65	5.16	0.333	0.167
	0.04	0.999	3.65	5.16	0.333	0.167
	0.08	0.997	3.65	5.16	0.427	0.186
	0.16	0.987	3.65	5.16	0.855	0.372
	0.32	0.947	3.65		1.710	
	0.50	0.866	3.65		2.670	
160	0.02	0.819*	5.16	7.31	0.333	0.167
	0.04	0.999	5.16	7.31	0.333	0.167
	0.08	0.997	5.16	7.31	0.605	0.263
	0.16	0.987	5.16	7.31	1.208	0.525
	0.32	0.946	5.16		2.420	
	0.50	0.866	5.16		3.780	
250	0.01	0.143*	6.46	9.15	0.333	0.167
	0.02	1.000	6.46	9.15	0.333	0.167
	0.04	0.999	6.46	9.15	0.378	0.167
	0.08	0.997	6.46	9.15	0.756	0.328
	0.16	0.987	6.46	9.15	1.512	0.658
	0.32	0.947	6.46		3.024	
	0.50	0.866	6.46		4.730	

^a(d/D) $\sqrt{D/T}$ is between 0.1414 and 0.2828 where number is followed by asterisk; ϕ_3 = fillet radius at intersection of triangular pad with the nozzle; ϕ_4 = fillet radius at intersection of triangular pad with the shell; A = cross-sectional area of reinforcement; and θ = acute angle of intersection of pad with nozzle. See Table 12 for definitions of other terms.

Table 15. Models analyzed in study of moment loading of nozzles in spherical vessels with fillet-radius reinforcing, $d_i/t = D_i/2T$

Model No.	Parameter ^a				
	D_i/T	d_i/D	ϕ_o/T	$\phi_o/\sqrt{d_i t}$	$2A_f/d_i T$
20	10	0.01	0.25	5.62	0.246
21	10	0.02	0.25	2.81	0.119
22	10	0.04	0.25	1.40	0.565
8	10	0.08	1.72	4.82	0.888
23	10	0.16	3.22	4.50	0.987
24	10	0.32	6.82	4.78	0.947
25	10	0.50	15.9	7.13	0.866
1	20	0.01	0.25	3.96	0.126
2	20	0.02	0.25	1.98	0.0616
3	20	0.04	1.11	4.40	0.515
4	20	0.08	2.47	4.90	0.997
5	20	0.16	4.16	4.12	0.987
6	20	0.32	8.35	4.14	0.947
7	20	0.50	16.9	5.35	0.866
14	640	0.01	3.72	10.4	1.00
16	640	0.02	5.67	7.94	1.00
17	640	0.04	8.30	5.82	0.999
13	640	0.08	12.35	4.32	0.997
18	640	0.16	19.4	3.39	0.987
19	640	0.32	34.2	2.99	0.947
15	640	0.50	56.4	3.15	0.866
8	10	0.08	1.72	4.82	0.888
4	20	0.08	2.47	4.90	0.997
9	40	0.08	3.36	4.70	0.997
10	80	0.08	4.60	4.45	0.997
11	160	0.08	6.36	4.55	0.997
12	320	0.08	8.83	4.37	0.997
13	640	0.08	12.35	4.31	0.997

^a A_f = cross-sectional area of reinforcing provided by the fillet; ϕ_o = outer radius of the nozzle attachment fillet. See Table 12 for definitions of all other terms.

Table 16. Models analyzed in study of moment loading of nozzles in spherical vessels with uniform-wall reinforcing on vessel or uniform-wall reinforcing on nozzle, ^a $\phi_o/T = 0.25$

Model No.	T'/T (h)	D_i/T	D_i/T'	d_i/D_i	$\phi_o/\sqrt{d_i t}$	$2A_f/d_i T$
26	1.0	200	200.0	0.01	1.25	0.013
27	1.0	100	100.0	0.0141	1.25	0.018
28	1.0	40	40.0	0.0224	1.25	0.028
29	1.0	20	20.0	0.0316	1.25	0.038
30	1.0	10	10.0	0.0447	1.25	0.050
31	1.5	1000	667.0	0.016	0.52	0.004
32	1.5	250	167.0	0.034	0.49	0.007
33	1.5	50	33.3	0.097	0.39	0.010
34	2.0	500	250.0	0.031	0.51	0.003
35	2.0	250	125.0	0.069	0.32	0.005
36	2.0	50	25.0	0.22	0.23	0.006
<hr/>						
	t'/t (g)					
37	3.0	200	200.0	0.01	1.25	0.013
38		50	50.0	0.022	1.14	0.023
39	6.0	200	200.0	0.011	1.13	0.012
40		50	50.0	0.025	1.00	0.019
41	12.0	250	250.0	0.01	1.12	0.010
42		100	100.0	0.024	0.74	0.010

^a A_f = cross-sectional area of reinforcing provided by the fillet. Models 26-30 do not require reinforcing. Reinforcing is provided by increase in vessel wall (models 31-36) or increase in nozzle wall (models 37-42); t' = wall thickness of nozzle with uniform-wall reinforcing on nozzle; T' = wall thickness of spherical vessel with uniform-wall reinforcing on vessel. See Table 12 for definitions of all other terms.

Fig. 1. Cylinder-to-cylinder shell model 1 and table showing dimensions of four models in test series.

directions at the free end of the nozzle and at the free end of the cylinder, and forces corresponding in directions and points of application to the moments. The thin-shell finite-element program JOINT is used to analyze the models as the test data become available. These data are also used to evaluate the closed-form type of analysis which is under development for the nozzle-to-cylindrical shell configuration.

As part of the nonradial nozzle analysis development work, the method of analysis developed at Auburn University (Shaw) is being extended for use in analyzing the University of Tennessee (Maxwell) 22 1/2 and 45° nonradial nozzle models. Each of these models is analyzed as the data become available. An analysis is being developed for a torispherical shell which has a radial nozzle at its apex; the torispherical shell is attached to a cylindrical vessel. Results from two experimental models are used to provide analysis verification information.

In addition to these studies, some of the models tested under other parts of the program are fabricated and instrumented at ORNL.

Accomplishments

The equations for a closed-form type of stress analysis were derived for cylindrical vessels having individual radial nozzle attachments subjected to either internal pressure or out-of-plane bending moments applied to the nozzle. These equations are applicable to thin-walled models for which the nozzle-to-shell diameter ratio is $\leq 1/3$. By use of the computer program form of the internal pressure analysis, comparisons were made with experimental data.

The analysis method for internal pressure and the associated computer program are in final form, and a report is being prepared which includes comparisons with data from the ORNL thin-shell steel model 4 ($D_o/T = 50$, $d_o/t = 20.16$, and $d_o/D_o = 0.129$). This work on developing equations and computer programs for calculating stresses in cylinder-to-cylinder connections is an extension of the analysis development work initiated at General Technology Corporation.

The initial analysis method for nozzle-to-cylindrical shell configurations under out-of-plane bending moments applied to the nozzles was found to be unsatisfactory. Therefore the equations for this case have

been redeveloped to employ a least-squares point-matching technique to satisfy boundary conditions along the nozzle-vessel intersection.

In the experimental study of steel nozzle-to-cylindrical shell models, models 1 and 3 (see Fig. 1 for dimensions) have been tested. Model 4, which was formed by reducing the 0.168-in. wall thickness of model 3 to 0.064 in., has been subjected to internal pressure loading and both in-plane and out-of-plane bending moment loadings applied to the nozzle. The experimental studies of these models are funded under a different program.

The thin-shell finite-element program JOINT was made operational on the ORNL computers and was used to analyze the thin-walled nozzle-to-cylindrical shell models that have been tested. Comparisons between theoretical and experimental results for model 1 have been published (12). A similar report of comparisons for model 3 is in preparation, and comparisons for three of the loadings are given in Project Report 7.

An axisymmetric finite-element computer program, SAFE-2D, was used to conduct a limited parameter study of compact reinforcement for radial nozzle-to-spherical shell attachments under internal pressure loading. The parameters studied were diameter-to-thickness ratios of the nozzles and the spherical shell and various combinations of inside and outside reinforcement.

A single machined 45° lateral which was eventually plastic collapse tested at the University of Waterloo (model Y₂, Table 8) was instrumented with 16 three-gage strain rosettes and tested elastically at ORNL. This lateral, having the parameters $D_i/T = 26.8$, $d_i/D_i = 1.0$, and $s/S = 1.0$, was machined from solid carbon steel stock. The flat plate models having 1, 2, 3, and 5 closely spaced holes which were tested at the University of Tennessee and those having 1, 2, and 5 closely spaced nozzles which were tested at Auburn University were fabricated and partially instrumented at ORNL.

A limited finite-element parameter study was made to evaluate the effect of varying the radii of circumferential fillets in the transition regions of cylindrical shells with a step change in outside diameter and loaded with internal pressure. The parameters studied, using the 27 models listed in Table 11, were ratios of thicknesses of the two sections,

ratios of fillet radius to thickness of the thinner section, and ratios of inside radius to thickness for the thinner section. In addition, comparisons were made of experimental and theoretical results for two experimental models and between duplicate analyses made using two different finite-element computer programs. The study was completed and a report was published (11).

A series of parameter studies has been conducted at ORNL in support of code-rule development work at Battelle Memorial Institute. A study was made to determine if a shell type of analysis could be used to conduct an expanded parameter study of inside versus outside reinforcement for nozzle-to-spherical shell attachments. This type of analysis requires less time and is considerably less expensive to use than the finite-element type. The 14 models listed in Table 12 were analyzed using the ORNL version of the STATIC program for an internal pressure loading. The first seven models listed in the table are experimental models for which photoelastic data have been published; the remaining seven models were analyzed by the finite-element method. One experimental model, WN-10B, is a photoelastic model which was analyzed using both methods of analysis.

The models used in the extended parametric study of inside versus outside reinforcement are listed in Table 13. The models consist of four basic series. The first two models in each series have approximately 100% inside reinforcement in conjunction with different fillet radii. In the subsequent five models the reinforcement is shifted in steps from the inside to the outside, and the final model in each series has approximately 100% reinforcement on the outside. These models were analyzed for internal pressure loading using the STATIC code. The findings of this study, together with the results of the limited parameter study described previously, will be used to determine whether the use of inside reinforcement should be limited by code rules. A study of triangular pad reinforcement for radial nozzles attached to spherical shells was made also using the axisymmetric shell analysis program STATIC. The study was made to determine the effect of various transition radii at the junctions of the pad with the nozzle and the shell on stresses produced by internal pressure loading. The 33 models used in this study are listed in Table 14.

In a continuing series of studies of fillet and uniform wall reinforcing for nozzles attached to spherical shells, the basic series of models listed in Tables 15 and 16 were analyzed for internal pressure and for a pure bending moment applied to the nozzle. The results of these parameter studies have been transmitted to Battelle Memorial Institute (Rodabaugh) for use in the development of code rules.

An analysis method was developed to determine stresses in a torispherical head which has a radial nozzle attached at its apex (10). The loadings considered were internal pressure, axial thrust applied to the nozzle, and a bending moment applied to the nozzle. Comparisons were made between the developed analysis and experimental data. The buckling of torispherical shells under internal pressure was also studied.

The University of Tennessee (Maxwell) hemispherical shell model 807-003 having a single 7 7/8-in.-OD radial nozzle ($D_i/T = 80.35$, $d_i/D_i = 0.249$, and $t/T = 0.5$) was analyzed using the CERL-II computer code (1), which is based on thin-shell theory. The loadings considered were internal pressure and an axial thrust loading of the nozzle.

The analyses developed at Auburn University (Shaw) for internal pressure loadings of nonradial nozzle configurations were modified to include angles of obliquity greater than 20° and extended to include axial thrust and bending moment loadings of the nozzle. The University of Tennessee 2 5/8-in.-OD radial and 22 1/2° nonradial nozzle models 802-001 and 802-221, respectively ($d_i/t = 8.5$, $D_i/T = 80.35$, and $s/S = 0.233$), are being analyzed using the improved analysis.

Work Planned

Comparisons between calculated and experimental results for spherical and cylindrical shells will continue during FY 1973. These comparisons are used both to examine the accuracies of the theoretical methods and to direct future work.

Analyses of the various configurations of the University of Tennessee (Maxwell) 22 1/2° nonradial nozzle attached to a hemispherical vessel will continue. The capability of the present analysis will be extended to include nozzles having angles of obliquity of 45° .

Parametric studies will be conducted in conjunction with design code rule development work at Battelle Memorial Institute. Included are a thermal stress analysis of the nozzle-to-spherical shell models listed in Tables 15 and 16, a parametric study of closely spaced pairs of nozzles attached to flat plates, and an extension of the inside versus outside reinforcement parametric study to moment loadings. These parametric studies are discussed further in the Battelle Memorial Institute - I section of this report.

The method of analysis developed at Battelle Memorial Institute (Hulbert) for clusters of nozzles attached to flat plates will be used to analyze the one-, two-, and five-nozzle flat-plate models being tested at Auburn University. Also the development of a closed-form shell type of analysis for the out-of-plane moment loading of a nozzle attached to a cylindrical shell will be completed, and comparisons will be made with experimental results from the thin-walled nozzle-to-cylindrical shell model tests. The experimental study of model 4 of the ORNL nozzle-to-cylindrical shell models will be completed, and testing of model 2 of this series ($D_o/T = 100$, $d_o/t = 100$, and $d_o/D_o = 1$) will be initiated.

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2. W. L. Greenstreet and R. C. Gwaltney, "Experimental and Analytical Investigations of Nozzles," Nuclear Safety Program Ann. Prog. Rep. Dec. 31, 1967, ORNL-4228, pp. 326-33.
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8. R. C. Gwaltney and J. M. Corum, "Analytical Investigations of Compact Reinforcement for Radial Nozzles in Spherical Shells," paper 71-PVP-26, presented at the First National Congress on Pressure Vessels and Piping, ASME, San Francisco, Calif., May 10-12, 1971; also published in Trans. ASME, J. Eng. Ind. 93(4), 905-12 (November 1971).
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11. R. C. Gwaltney and J. W. Bryson, Effect of Fillets in Cylindrical Shells with Step Changes in Outside Diameter, ORNL-TM-3766 (May 1972).
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Battelle Memorial Institute - 1

Principal Investigator: E. C. Rodabaugh

Objective

Data developed under the ORNL Nozzles Program and other relevant programs are collected, evaluated, and correlated, and comparisons are made between theoretical results and experimental data to evaluate the accuracy of candidate analytical methods. The proven analytical methods are used together with experimental data to develop design rules for reinforced openings in pressure vessels which are suitable for inclusion in the ASME Boiler and Pressure Vessel Code and in RDT standards.

Description of Models

This correlation type of study is basically theoretical; however, available experimental data are included when possible. Considered in this study are several types of nozzle-to-vessel junctions consisting of reinforced and unreinforced individual nozzles attached to spherical and cylindrical shells as well as multiple-nozzle attachments.

Scope

Available information on specific nozzle-to-shell attachment configurations is collected and used to develop design rules suitable for incorporation into the various design codes. Rules are developed to cover both internal pressure loadings and combinations of internal pressure and externally applied nozzle loadings. Analytical parameter studies are conducted in cooperation with ORNL using the verified methods of analysis, and the resulting data are incorporated in the form of graphs and tables into proposed additions or revisions of the codes. Phase reports containing this information together with necessary supporting material are submitted to the Pressure Vessel Research Committee for review and transferal to appropriate code bodies. Additional tasks pertinent to the design of reinforced openings in pressure vessels will be included in accordance with program requirements.

Accomplishments

Reports containing comparisons between experimental and theoretical results, data correlations, and proposed design rules for radial nozzle-to-vessel attachments have been published. Separate reports have been published for internal pressure loadings and for combinations of internal pressure and moment loadings of the nozzle. The various reinforcement configurations thus far considered for spherical vessels and, to a limited extent, for cylindrical vessels are outside reinforcement, inside reinforcement, combinations of outside and inside reinforcement, triangular pad reinforcement, and uniform wall reinforcement.

A report consisting of a series of six BMI phase reports has been published (1). The report contains proposed design procedures for internal pressure loading of radial nozzles attached to cylindrical or spherical

shells along with tables and graphs for obtaining stresses for these two radial nozzle configurations. The report also discusses theories for analysis of combinations of internal pressure and externally applied nozzle loadings and various aspects of nozzle flexibility.

A review of service experience and test data on openings in pressure vessels with nonintegral reinforcing was prepared under this program (7). The location of critical stresses was identified, and the practice of postweld inspection is recommended. This report was recently published by the Welding Research Council (8).

Two reports were prepared on the elastic stress analysis of internal pressure loading of radial nozzle-to-vessel configurations (4 and 9). These reports contain results of parametric studies of triangular pad reinforcement, comparisons of finite-element and shell analyses, and analyses of nozzle-to-cylindrical shell attachments made using a closed-form shell type of analysis together with available test data. The fillet radii requirements of Section III of the ASME Code are discussed, and areas where the rules appear to be excessively restrictive are indicated.

Rules to be used as alternatives to those presently found in the ASME code for the design of reinforced radial nozzles attached to spherical or cylindrical vessels under internal pressure (5) have been adopted by the American Society of Mechanical Engineers and were published in the Winter 1971 Addenda to Section III and Section VIII, Division 2, of the ASME Boiler and Pressure Vessel Code.

Comparisons of finite-element and experimental results of a nozzle-to-spherical shell model were published (6). The report discusses through-the-wall stress variations, the influence of Poisson's ratio, and the relationship of photoelastic test data to the behavior of steel models.

The results of joint BMI-ORNL parameter studies of internal pressure and bending moment loadings of nozzle-to-spherical shell configurations are given in a recent report (10). Based on moment loadings allowed by the ASME code, it is shown that the resulting maximum stress may be produced by the moment rather than the pressure loading and that under certain conditions stresses due to moment and pressure loadings may not be additive.

The draft of a report containing results of joint BMI-ORNL parameter studies of inside versus outside reinforcing for nozzles attached to spherical shells has been completed. The stress indices prescribed by Section III of the ASME Code are shown to be unconservative when all reinforcing is placed inside the shell. It is recommended that the code be revised to require that a minimum percentage of the reinforcement be placed outside the shell.

Work Planned

The work of collecting and evaluating the information being developed under the ORNL Nozzles Program and other programs will continue, and proposed code rule additions and modifications will be prepared. Studies planned for FY 1973 include those pertaining to elastic analysis of clusters of nozzles and to plastic limit analysis of individual nozzle-to-shell attachments. Parametric studies will be conducted in cooperation with ORNL, and the resulting information will be evaluated in light of current code practice. Code rule changes will be prepared as specific needs are identified.

Owing to technical problems, a satisfactory shell-type of analysis for nozzle-to-cylindrical vessel attachments is unavailable at present. Therefore, a parametric study will be made to determine if widely accepted axisymmetric analytical methods are applicable to restricted parameter ranges of the nonaxisymmetric nozzle-to-cylinder configuration.

It is fairly common design practice to use uniformly reinforced nozzles with the required reinforcement contained in the uniform wall section of the nozzle. Parameter studies will be made of a series of so-called "standard" nozzle-to-shell configurations having uniform reinforcement, with the range of parameters to be employed determined from information supplied by a cross section of pressure vessel designers.

A report will be prepared on the design of closely spaced nozzles according to Section III of the ASME code. Available experimental data will be reviewed, and, depending upon the availability of a satisfactory analysis, parameter studies will be conducted at ORNL.

The study of single nozzle-to-spherical vessel attachments under internal pressure loading will be completed, and studies of combined

loadings will be continued. A study will also be made of stresses resulting from thermal gradients on nozzle-to-spherical shell configurations.

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9. E. C. Rodabaugh and R. C. Gwaltney, Phase Report 117-2 on Additional Data on Elastic Stresses in Nozzles in Pressure Vessels with Internal Pressure Loading, Battelle Memorial Institute (December 1971).
10. E. C. Rodabaugh and R. C. Gwaltney, Phase Report 117-6R on Elastic Stresses in Nozzles in Spherical Pressure Vessels with Pressure and Moment Loading, Battelle Memorial Institute (August 1972).

PART 2. AEC (ORNL)-SPONSORED PROGRAM

The work included under this part of the overall Nozzles Program consists primarily of experimental and theoretical studies of multiple-nozzle configurations. In general, the experimental work parallels the development of corresponding analyses. The program consists of studies of flat plates and spherical vessels having closely spaced clusters of holes or nozzles.

This section contains summaries of the various studies being conducted by the participating organizations under AEC (ORNL) sponsorship. As in Part 1 of this report, each study is described with respect to its objectives, the types of models being studied, the scope of the work, the progress achieved through FY 1972, and the work planned for FY 1973.

University of Tennessee - II

Principal Investigator: A. Mathews

Objective

A series of instrumented steel flat plates containing clusters of holes is tested under uniaxial and biaxial loadings, and the resulting data are used primarily in analysis development and verification.

Description of Models

The basic $36 \times 36 \times 0.375$ in. flat-plate model along with the one-, two-, three-, and five-hole geometries tested are shown in Fig. 2. In addition to these models, two instrumented unpierced flat plates of the same size and type as shown in the figure are being tested to evaluate the loading system.

Each of the carbon steel plates is instrumented with bonded electrical resistance strain gages in the region of the holes. The number of individual strain gages used range from 81 for the one-hole model to 201 for the five-hole model.

Fig. 2. Hole-cluster pattern and details for flat-plate models.
All plates are 3/8 in. thick.

Scope

In the stress analysis of relatively small nozzles attached to large-radius cylindrical or spherical vessels, vessel curvature may have little influence on stresses resulting from internal pressure and external loadings applied to the nozzles. Consequently, flat plates can be used to study the effects of penetrations in large-radius vessels. The results of tests on models of this type are used in the development and verification of analyses. This work is an important first step toward the development of satisfactory analyses for clusters of nozzles attached to pressure vessels.

In the project to investigate small nozzle attachments, in-plane-loaded perforated plates are tested initially to provide information on stress and strain distributions around holes in shells under membrane loadings and to provide data for development of theoretical methods of analyses. The resulting analysis methods are then to be extended stepwise to apply to nozzle clusters. The tests consist of subjecting perforated plates to uniaxial and biaxial loadings by means of 32 hydraulic rams positioned eight to a side along the edges. Each plate is instrumented on one side only and tested in a horizontal orientation; consequently, each loading is conducted with the gaged side of the plate up and repeated with the plate in an inverted position. The results of the two loadings are averaged to eliminate plate bending and possible eccentricities in the loading system.

In addition to a uniaxial loading, each plate is subjected to both a 1:1 and a 2:1 biaxial loading to simulate stresses due to internal pressure loading of spherical and cylindrical vessels.

Accomplishments

The proposed tests have been completed. A plate containing a four-hole cluster was included in the original scope of work, but this model was eliminated when it was determined that it was not required for development and verification of analysis methods. In addition to uniaxial and biaxial testing of the plates, 12 tensile specimens cut from the material used in the fabrication of these plates were tested. No significant

differences could be determined between the moduli of elasticity or Poisson's ratios in the rolling direction and perpendicular to the rolling direction.

The experimental results of the one-, two-, three-, and five-hole models were processed and published in separate reports. The reports also include preliminary comparisons that were made using calculated results from the flat-plate analysis developed under this program at Battelle Memorial Institute as well as comparisons between biaxial loading results and results obtained by superposition of experimental data for uniaxial loadings to produce the desired biaxial loadings.

Work Planned

This study was satisfactorily completed in 1971 (FY 1972), and no additional work is planned. The follow-on study of clusters of nozzles attached to flat plates is being conducted under subcontract at Auburn University.

Project Reports

1. A. Mathews, Experimental Stress Analysis of Clusters of Holes of Equal Diameters in Flat Plates - Part I, A Single Hole, Report EM-69-2, University of Tennessee, Department of Engineering Mechanics (April 1969).
2. A. Mathews and R. B. Michaels, Experimental Stress Analysis of Clusters of Holes of Equal Diameters in Flat Plates - Part II, Two Holes, Report EM-70-2, University of Tennessee, Department of Engineering Mechanics (June 1970).
3. A. Mathews, R. B. Michaels, and R. J. Warmack, Experimental Stress Analysis of Clusters of Holes of Equal Diameters in Flat Plates - Part III, Three Holes, Report EM-70-3, University of Tennessee, Department of Engineering Mechanics (October 1970).
4. A. Mathews, R. B. Michaels, and R. J. Warmack, Experimental Stress Analysis of Clusters of Holes of Equal Diameters in Flat Plates - Part IV, Five Holes, Report EM-71-3, University of Tennessee, Department of Engineering Mechanics (June 1971).

Battelle Memorial Institute - II

Principal Investigator: L. E. Hulbert

Objective

Theoretical methods of elastic stress analysis and associated computer programs are developed for (1) perforated square flat plates, (2) clusters of nozzles attached to square flat plates, and (3) clusters of nozzles attached to spherical shells. The analytical method development is being done in three steps corresponding to the three basic types of models to be considered. As each step is completed, the theoretical results are compared with corresponding experimental results obtained at the University of Tennessee and at Auburn University to verify the analysis.

Once the analyses are verified, they are used at ORNL for conducting parameter studies of stresses and displacements in the attachment regions of nozzle clusters. The results of the flat-plate studies are applicable to clusters of small-diameter nozzles attached to large-radius thin-walled vessels.

Description of Models

The four basic types of models to be used for analysis verification in this purely analytical study are:

1. square flat plates containing closely spaced clusters of one, two, three, and five holes and having the same basic hole geometries as the experimental models tested at the University of Tennessee (Mathews);
2. square flat plates having closely spaced clusters of one, two, and five attached nozzles, with the same basic cluster geometries as the flat-plate experimental models tested at Auburn University (Swinson);
3. spherical shells having clusters of two, three, four, and five holes, with the same basic dimensions as the hemispherical shell with four clusters of holes tested at Auburn University (Swinson);
4. spherical shells having closely spaced clusters of two, three, four, and five attached nozzles, with the same basic cluster geometries as

the two-, four-, and five-nozzle hemispherical shell experimental models tested at Auburn University (Swinson).

Scope

The work is divided into the following nine tasks:

1. perform membrane stress analyses of square plates with clusters of one, two, three, and five holes under uniaxial and biaxial (1:1 and 2:1 ratios) in-plane plate edge loadings using the computer program TABLES;
2. develop a computer program, PEBBLES, to analyze the bending of plates as a result of loadings applied normal to the plate and around the edges of the holes;
3. modify an existing computer program, NØNLIN, for analyzing cylindrical shells to calculate sets of influence coefficients for the nozzles;
4. develop a matrix manipulation program, INTRTIE, to combine the matrix equations generated by TABLES, PEBBLES, and NØNLIN to calculate stresses, strains, and displacements of nozzle-to-plate attachments;
5. perform demonstration analyses of one, two, and five closely spaced nozzles attached to flat plates for uniaxial and biaxial (1:1 and 2:1) loadings of the plate and externally applied force and moment loadings of the nozzles;
6. use an existing analytical method to calculate results for internally pressurized perforated spherical shells with two-, three-, four-, and five-hole clusters;
7. develop a matrix manipulation program similar to INTRTIE to combine the matrix equations generated by the existing analysis for perforated spherical shells and by NØNLIN to calculate stresses, strains, and displacements of nozzle-to-spherical shell attachments;
8. conduct demonstration analyses of one, two, four, and five closely spaced nozzles attached to spherical shells for pressure loading of the shell and nozzle, and external force and moment loadings of the nozzles;
9. prepare comprehensive reports on each analysis method which will include a section to serve as a user's manual for the relevant computer programs.

There are two basic classes of problems considered in this study. Class 1 involves those geometries for which one nozzle or less is included in a symmetry element. Examples of problems in this class are the clusters of one, two, three, and four nozzles subjected to 1:1 in-plane biaxial plate edge loadings and the clusters of one, two, and four nozzles under uniaxial plate edge loadings.

Class 2 problems consist of geometries for which portions of more than one nozzle are included in a symmetry element. These problems are all loadings of the five-nozzle cluster and the uniaxial plate edge loading of the three-nozzle cluster. To insure that the methods being developed under this program are capable of analyzing both classes of problems, demonstration analyses will be performed for all loading conditions of the one-, two-, and five-nozzle clusters. By use of the methods developed, results for any combination of external loads and internal pressure can be obtained by superposition.

Accomplishments

The computer program TABLES was used to calculate membrane stresses around holes in flat plates having clusters of one, two, three, and five holes under uniaxial and biaxial (1:1 and 2:1) plate edge loadings.

The computer program INTRTIE was developed and used together with TABLES, PEBBLES, and NONLIN to analyze the one- and two-nozzle clusters. The loadings were internal pressure in the nozzle, and externally applied nozzle loadings consisting of axial thrust, shear, and bending moments combined with the uniaxial and biaxial plate edge loadings.

To provide an assessment of the results obtained using this analysis, a single nozzle attached to a circular plate was analyzed, and comparisons were made with results obtained using a well-established and verified program already in existence. Although these comparisons were favorable, it will be necessary to make comparisons with the experimental results for the one- and two-nozzle flat-plate models before the analysis can be considered to be verified.

The analysis has also been used to calculate results for a series of class 2 problems consisting of biaxial plate loadings, and axial thrust, shear, and bending moment loadings applied to the central nozzle of the

five-nozzle cluster attached to a square flat plate. Verification of the class 2 problems awaits the availability of experimental data from Auburn University.

Work Planned

The remaining loadings of the various nozzles in the five-nozzle cluster attached to the square flat plate will be completed during FY 1973, and a report that includes all additional information required to use the combined analysis on class 2 problems will be published.

Calculations will be made for pressurized perforated spherical shells with clusters of two, three, four, and five holes. Work will be initiated during FY 1974 on the development of the analysis method for clusters of two, three, four, and five nozzles attached to a spherical shell.

Project Reports

1. L. E. Hulbert, E. F. Rybicki, and A. T. Hopper, First Annual Report on the Stress Analysis of Clusters of Cylindrical Nozzles Attached to Large Spherical Shells, BMI-X-576, Battelle Memorial Institute (Sept. 29, 1969).
2. L. E. Hulbert, A. T. Hopper, and E. F. Rybicki, Second Annual Report on the Stress Analysis of Perforated Plates and Plates with Single and Clustered Nozzles, Battelle Memorial Institute (Oct. 9, 1970).

Auburn University - I

Principal Investigator: W. F. Swinson

Objective

A series of experimental studies are made of spherical shells. Of interest are stresses in the vicinities of closely spaced holes and in the attachment regions of nozzle clusters. The former are to provide data for analysis method development, and the latter are for the dual purpose of providing a better understanding of the interaction of closely spaced nozzles and furnishing data to be used in the verification of analytical techniques. In addition, flat plates with clusters of attached nozzles are under experimental investigation. Configurations under study include

square flat plates having attached clusters of one, two, and five nozzles; a hemispherical shell with closely spaced clusters of two, three, four, and five holes; and hemispherical shells having attached clusters of two, four, and five nozzles.

Description of Models

The models being studied are listed in Table 17. All the flat-plate models, including three tested at the University of Tennessee (Mathews), are listed for completeness. The two unpierced models and the perforated flat-plate models, 3P1, 3P2, 4P, and 5P, were tested at the University of Tennessee; the second unpierced plate, model 2P, was retested at Auburn University. Table 18 contains additional model dimensions together with the dimensionless parameters.

The flat-plate model having a single nozzle attachment, model 6P, is shown in Fig. 3, together with the two-nozzle (7P) and five-nozzle (10P) cluster arrangements. The $36 \times 36 \times 0.375$ in. steel plates are instrumented with bonded strain gages in the nozzle region. The number of strain gages employed in each test depends upon the complexity of the geometry with approximately 300, 500, and 900 individual gages being used on the one-, two-, and five-nozzle models respectively.

A hemispherical vessel, designated as model AUI, is used to study strain distributions around four separate clusters of holes when the vessel is pressurized. This 40.90-in.-OD vessel is divided into quadrants containing two-, three-, four-, and five-hole clusters arranged as shown in Fig. 4. The 1.572-in.-diam holes are radial in orientation, and each cluster is centered at a vertical angle of 47° from the base of the model to avoid possible influences of vessel flange on the strain field in the vicinity of the holes. Each hole is sealed by a piston and O-ring during the internal pressure test of the vessel. The vessel is instrumented on both inside and outside surfaces with approximately 700 bonded electrical resistance strain-gage elements in the form of three-gage rosettes which are positioned along lines radial to the holes.

A second steel hemispherical vessel, model AUII, is used to study clusters of closely spaced radial nozzles. The model, having dimensions as shown in Table 17, was initially fabricated with two 7.002-in.-OD radial

Table 17. Experimental investigations of hole and nozzle clusters in shells
(See Table 18 for model dimensionless parameters)

Specimen	Number	Configuration	Holes or nozzles				Nozzle dimensions (in.)			
			Diameter ^a (in.)	Pattern	Clear spacing (in.)		Length		Thickness	Mean radius
					Minimum	Maximum	Outside	Inside		
Flat plate ^b (36 × 36 × 3/8 in.)	1P ^c	Unpierced								
	2P ^{c,d}	Unpierced								
	3P ^c	One hole	2.625							
	3P2 ^c	Two hole	2.625		0.375					
	4P ^c	Three hole	2.625	Triangular	0.375					
	5P ^c	Five hole	2.625	Square ^e	0.375	1.625				
	6P ^d	One nozzle	2.625				8.5	0.0	0.250	1.188
	7P ^d	Two nozzle	2.625		0.375		8.5	0.0	0.250	1.188
	10P ^d	Five nozzle	2.625	Square ^e	0.375	1.625	8.5	0.0	0.250	1.188
Hemisphere (D _o = 40.90 in., T = 0.503 in.)	AUI	Two hole	1.572		0.540					
	AUI	Three hole	1.572	Triangular	0.825					
	AUI	Four hole	1.572	Square	1.138	2.246				
	AUI	Five hole	1.572	Square ^e	1.539	2.804				
Hemisphere (D _o = 41.19 in., T = 0.500 in.)	AUII	Two nozzle	7.002		3.603		10.0	0.0	0.333	3.33
	AUII	Four nozzle	7.002	Square	3.603	8.110	10.0	0.0 ^f	0.333	3.33
	AUII	Five nozzle	7.002	Square ^e	0.553	3.603	10.0	10.0 ^f	0.333	3.33

^aOuter diameter (d_o) for nozzles.

^bAll flat plates are listed for reference purposes.

^cModels tested at the University of Tennessee.

^dModels tested at Auburn University.

^eOuter nozzles in square pattern with fifth nozzle positioned in center.

^fNozzle dimensions are based on 5.25-in.-OD, 0.25-in.-wall thickness University of Tennessee nozzle (not used).

Fig. 3. Nozzle design and cluster-pattern details for Auburn University flat-plate models. All plates are 3/8 in. thick.

ORNL-DWG 70-14152A

2-HOLE QUADRANT

3-HOLE QUADRANT

4-HOLE QUADRANT

5-HOLE QUADRANT

Fig. 4. Hole arrangement in Auburn hemispherical vessel model AUI.
(See Tables 17 and 18 for a complete listing of dimensions.)

Table 18. Dimensionless parameters for Auburn University models with closely spaced holes and nozzles

Model No.	Configuration	D_o/T	r_m/t	T/t	t/T	d_i/D_i	s/S
6P	1-nozzle		4.75	1.50	0.67		
7P	2-nozzle		4.75	1.50	0.67		
10P	5-nozzle		4.75	1.50	0.67		
AUI	2-hole	81.40				0.039	
AUI	3-hole	81.40				0.039	
AUI	4-hole	81.40				0.039	
AUI	5-hole	81.40				0.039	
AUII	2-nozzle	82.23	10.00	1.50	0.67	0.164	0.474
AUII	4-nozzle	82.23	10.00	1.50	0.67	0.164	0.474
AUII	5-nozzle	82.23	10.00	1.50	0.67	0.164	0.474

nozzles attached to the vessel at the locations designated by test 1 in Fig. 5. These nozzles were attached flush with the inside of the vessel using full penetration welds. The welds were subsequently reduced to essentially a zero fillet radius at the nozzle-vessel junction to produce an idealized configuration.

The finished two-nozzle model is instrumented with approximately 420 strain-gage elements along the inside and outside surfaces of both nozzle and vessel. Upon completion of the testing of the two-nozzle configuration, model AUII is modified by attaching two additional nozzles at the test 2 locations shown in Fig. 5, thereby forming the four-nozzle configuration. Once the new configuration is fabricated, approximately 330 additional strain-gage elements will be attached to the model.

The final configuration for model AUII will be produced when testing of the four-nozzle configuration is completed by adding a fifth nozzle to the vessel at the test 3 position of Fig. 5. Approximately 200 strain-gage elements will be added to the model when the five-nozzle configuration has been fabricated.

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Fig. 5. Auburn University model AU11 with layout of large holes for five radial nozzles. (See Tables 17 and 18 for a complete listing of dimensions.)

Scope

This investigation encompasses a perforated hemisphere as well as both flat plates and hemispherical shells having closely spaced nozzles. The three flat-plate models included in this study are the next step in degree of complexity to the perforated flat plates tested at the University of Tennessee and listed in Table 17. In addition to uniaxial and biaxial plate loadings used in both flat-plate studies, the attached nozzles are subjected to axial thrust and bending moment loadings.

In addition to providing a better understanding of the behavior of clusters of nozzles, the tests are to provide data for verifying theoretical analyses being developed at Battelle Memorial Institute (Hulbert). From the analytical standpoint, another important test is that of the perforated hemispherical model (AUI) under internal pressure loading.

The most complex models to be considered in this investigation are the AUII hemispheres having attached clusters of two, four, and five nozzles. Each of these configurations is subjected to an internal pressure loading and various nozzle loadings consisting of axial thrust and bending moments. Each nozzle configuration is designed with as much flexibility as possible so that subsequent modifications such as reducing the nozzle wall thickness can be undertaken to provide additional information as needed for the verification of analyses.

Accomplishments

Testing of the one- and two-nozzle flat-plate models has been completed. Each model was tested under in-plane biaxial loadings of the plate consisting of (1) a 1:1 loading, that is, equivalent loadings along adjacent edges of the plate at two different stress levels, (2) a 1:2 loading, and (3) a 2:1 loading for the two-nozzle model. Once the biaxial series of loadings were completed, the plates were restrained along the edges of the test framework, and the models were subjected to axial thrust and bending moment loadings of the nozzle. For the in-plane biaxial studies, the plates were oriented vertically to eliminate bending effects caused by the weight of the plate itself.

The flat-plate model with a five-nozzle cluster has been instrumented, and testing is in progress. This model was partially instrumented with strain gages at ORNL prior to being transported to the test site.

Internal pressure testing of the perforated hemispherical shell model AUI has been completed, and the data are being processed. The computer program for data reduction and plotting developed at the University of Tennessee (Maxwell) under the Nozzles Program has been adapted for use in processing all Auburn University data. The program is thus being used to process data from the flat-plate and hemispherical shell models.

The two-nozzle configuration of model AUII has been tested, and the results have been published (5). This report, which contains results of internal pressure loading and nozzle loadings, consisting of axial thrust and bending moments, is the first report by Auburn University to be completed using the recently modified University of Tennessee computer data processing procedure.

Model AUII has been modified to include two additional nozzles, thereby forming the four-nozzle configuration. Modification of the model is complete, and the new configuration is being instrumented with strain gages.

Work Planned

During FY 1973 the reports on the one- and two-nozzle flat-plate models and on the perforated hemispherical shell model will be completed. Testing of the flat-plate model with the five-nozzle attachment will be completed, and the four-nozzle configuration of model AUII will be instrumented with additional strain gages and testing initiated.

Project Reports

1. C. E. Kennedy and W. F. Swinson, Experimental Investigations of Closely Spaced Nozzles Attached to a Spherical Shell, Progress Report, Auburn University (Apr. 13, 1967).
2. R. W. Aderholdt and W. F. Swinson, Experimental Investigations of Closely Spaced Nozzles Attached to a Spherical Shell, Progress Report, Auburn University (Apr. 24, 1968).

3. R. W. Aderholdt and W. F. Swinson, Experimental Investigations of Closely Spaced Nozzles Attached to a Spherical Shell, Progress Report, Auburn University (Jan. 31, 1969).
4. R. W. Aderholdt, Stress Distributions in Thin Walled Pressure Vessel with Closely Spaced Nozzles by Scattered Light Photoelasticity, Master's thesis, Auburn University, March 1969.
5. R. W. Aderholdt, W. F. Ranson, and W. F. Swinson, Experimental Stress Analysis of Spherical Pressure Vessels with Closely Spaced, Large Radial Nozzles Attached, Parts I and II, Report ME-UC2670-1, Revised, Auburn University (March 1972).