BUCKLING OF CYLINDRICAL SHELLS WITH REINFORCED CIRCULAR OPENINGS UNDER AXIAL COMPRESSION

by

Clarence D. Miller
Director of Structural Research

and

Robert B. Grove
Research Engineer

Chicago Bridge & Iron Company
Plainfield, Illinois

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INTRODUCTION

Many buckling tests have been performed on cylindrical shells with unreinforced circular and rectangular openings (2, 3, 6, 7, 8) and several tests with reinforced rectangular openings (2, 4). Several numerical studies have also been made of shells with the geometry and type of reinforcement corresponding to the test shells (1, 2, 4) and one study has been made of ring and stringer stiffened shells with rectangular openings (5). None of these studies consider the effect on buckling of openings that are reinforced by the area replacement rules of the ASME Code (9).

Babcock (3) performed a series of tests which considered the extreme cases of circular opening with no reinforcement and with a rigid penetration. He also performed a set of tests with a flexible penetration. None of these tests were made on shells with reinforcement added along the cylinder wall. This method is often used for reinforcement of openings in containment and other type pressure vessels.

The present study was performed to determine the effect on buckling of adding reinforcement along the cylinder wall as well as normal to the cylinder wall. The limits of reinforcement were determined in accordance with the ASME Code (9). Tests were performed on a 15 in. diameter cylinder with a 4 in. diameter opening. The opening corresponds to a 30° central angle which is the largest opening that has been considered for a containment vessel.

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[1]Director of Research and [2]Research Engineer, Chicago Bridge and Iron Company, Plainfield, Illinois

NOTATIONS

A = Cutout Area

A_r = Effective Area of Reinforcement

E = Modulus of Elasticity of the Material

L = Unsupported Length of Cylinder

P = Failure Load

P_{CL} = Classical Buckling Load, $0.605E(t/R)\ 2\pi Rt$

P_o = Failure Load for Cylinder Without Cutout

R = Centerline Radius of Cylinder

r = Cutout Radius

r_n = Centerline Radius of Nozzle

t = Cylinder Wall Thickness

t_e = Reinforcing Pad Thickness

t_n = Nozzle Wall Thickness

EXPERIMENTAL PROGRAM

The experimental work was conducted on a cylinder made from mylar. This material was selected because the test cylinder could be buckled many times without permanent damage and still provide reproducible results. The stress-strain curve remains linear for stresses well above the buckling stresses of the test cylinders. The loading considered in these tests was uniform axial compression.

The test shell was constructed from a flat sheet of mylar cut to the appropriate size. The ends were secured in steel clamping rings used on previous tests on steel cylinders (10).

The test shell was fitted into the bottom clamping ring. The upper clamping ring was then installed and aligned to make the two clamping rings parallel. After alignment, the mylar sheet was secured to the clamping rings. The use of clamping rings resulted in a cylinder with larger imperfections than was found on similar shells with the ends secured to the end plates with a low melting temperature alloy. The buckling capacity of the shell is, however, more representative of a fabricated shell. The cylinder was completed by making a butt joint with both sides reinforced by 1.0 in. wide mylar strips attached with Scotch brand double stick tape. The resulting cylinder was 15.0 in. inside diamter, 0.0132 in. wall thickness, and 15.0 in. clear span between clamping rings. The modulus of elasticity was determined in accordance with ASTM D88L-75b and found to be 650,000 psi. The stress-strain curve is shown in Fig. 1. Poisson's ratio was assumed to be equal to 0.3.

The cylinder was tested on a 120,000 lb. Tinius-Olsen "Electromatic Universal Testing Machine". The machine is equipped with a swivel head attachment that allows the load to be applied without any eccentricity. A 16 inch diameter steel block was attached to the swivel head which transmits the load to the upper clamping ring. The test apparatus can be seen in the various figures of the failed test cylinder.

The cylinder was first tested without any cutout. A 4 in. diameter cutout was then made and the cylinder re-tested. Successive tests were made by attaching 0.25 in. wide x 0.0132 thickness reinforcing pads around the cutout with Scotch brand double stick tape

to replace the cutout area. A second series of tests were made using one reinforcing pad and adding reinforcement in the form of a nozzle penetration. The first nozzle thickness was attached to the cylinder shell and reinforcing pad with Scotch-Weld structural adhesive 2216 B/A gray. Successive layers of nozzle wall thickness were attached using Scotch Brand double stick tape. The effective area of reinforcement was determined in accordance with the ASME Code (9). For limits of reinforcement for test cylinder see Fig. 2. The geometry of the cylinder and reinforcement is shown in Fig. 3.

EXPERIMENTAL RESULTS

The results of the present tests are given in Table 1. Tests by others (3, 6, 8) show that the buckling capacity of a cylindrical shell with an unreinforced cutout is a function of the parameter $\gamma = r/\sqrt{Rt}$. A plot of this data is shown in Fig. 4. Tests 1A where $\gamma = 0$ and 1B where $\gamma = 6.36$ are also shown in Fig. 4.

Test 1A failed at 29% of the classical buckling value compared to a range of 60 - 97% for other investigators. The lower buckling value of 1A is due to larger initial imperfections and different end restraint conditions. The proposed ASME Appendix for design of containment vessels (11) gives a value of $P/P_{CL} = 0.22$ for a fabricated steel shell.

The tests by Starnes (6, 7) show that P/P_{CL} falls in a range of 0.20 - 0.30 for $\gamma = 6.36$. Test 1B failed at $P/P_{CL} = 0.22$ which is within the range of the tests by Starnes.

The effect of replacing the cutout area is demonstrated in Fig. 5 where P/P_o is plotted vs. A_r/A. It is interesting to note that adding reinforcement to the cylinder wall was more efficient than adding it to the penetration wall. A value of $P/P_o = 0.9$ was obtained at a value of $A_r/A = 0.4$ for either type of reinforcement. There was no appreciable increase in the buckling load for values of A_r/A = 0.40 - 0.77 when added to the penetration wall. When additional area was added to the cylinder wall the buckling capacity continued to increase until $P/P_o = 1.0$ at a value of $A_r/A = 0.86$. Tests by Babcock (3), who used a rigid plug which more than replaced the cutout area, showed a maximum value of $P/P_o = 0.95$. The tests on cylinders with rectangular openings (2) compare favorably with those on cylinders with circular openings.

Several photographs of buckled cylinders are shown in Fig. 6. The failure patterns were very nearly the same for all tests. Away from the opening the buckling pattern was identical to that of the shell without a cutout.

CONCLUSIONS

If a cutout in a cylinder loaded by axial compression is small enough initial imperfections and end restraint conditions will govern the buckling load. As the cutout size increases, the effects of the cutout become greater than that of the initial imperfections and end restraint conditions. Tests by Starnes (6, 7) show that the buckling load of the cylinder is reduced when $\gamma > 0.5$.

Only a value of $\gamma = 6.36$ was investigated in the present study. The buckling value of the unreinforced opening was 22% of the classical buckling load. This value is within the scatter band of tests by Starnes.

The buckling capacity of a cylinder with a cutout can be increased by adding reinforcement. By replacing 40% of the cutout area the buckling capacity was increased to 90% of the value of the cylinder without a cutout. By adding 86% of the cutout area to the cylinder wall the buckling capacity was equal to that of the cylinder without a cutout. There was no appreciable increase in the buckling capacity for values of $A_r/A > 0.4$ when the reinforcement was added to the penetration wall.

The penetration wall was attached with material having greater flexibility than the penetration and shell material. Possibly the effective penetration area was not fully developed.

The buckling patterns of the cylinders away from the opening were the same for all tests and corresponded to that of the cylinder without an opening.

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TABLE 1 - SUMMARY OF TEST RESULTS

TEST	t_e	t_n	A_r/A	P/P_{CL}	P/P_o
1A	NO HOLE		-	.292	1.000
1B	0	0	0	.223	.764
1C	.0134	0	.125	.252	.863
1D	.0267	0	.250	.258	.884
1E	.0400	0	.374	.264	.904
1F	.0533	0	.499	.273	.935
1G	.0663	0	.620	.275	.942
1H	.0794	0	.743	.284	.973
1I	.0926	0	.866	.300	1.027
1J	.1059	0	.990	.301	1.031
1K	.0134	0	.125	.237	.812
1L-A	.0134	.0125	.205	.223	.764
1M-A	.0134	.0253	.350	.259	.887
1N-A	.0134	.0377	.530	.264	.904
1Ø	.0134	.0502	.742	.264	.904

R = 7.507 in.   t = .0132 in.   L = 15.0 in.   E = 650,000 psi

r = 2.0 in.

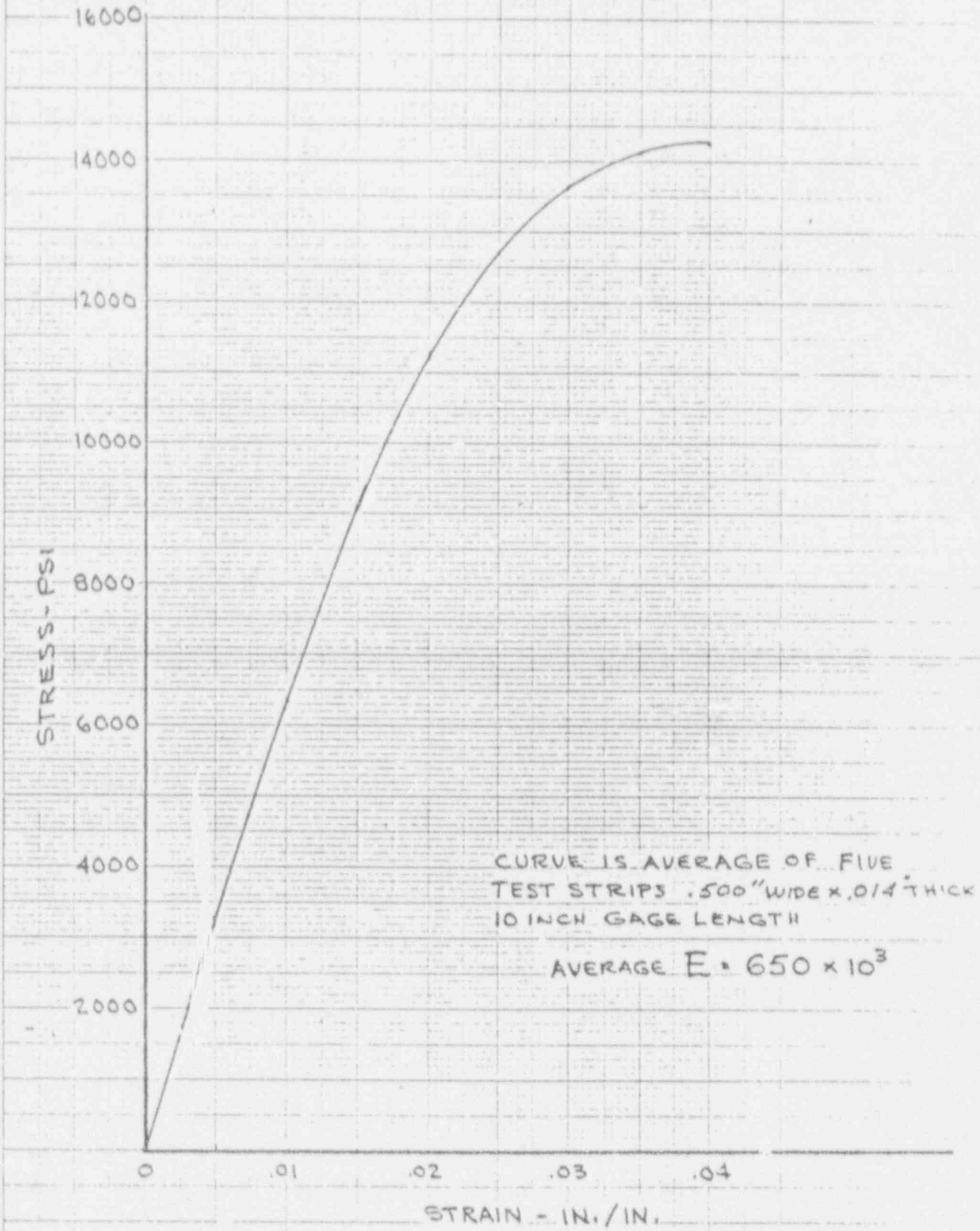


FIG. 1 - STRESS - STRAIN CURVE
MYLAR SHEETING

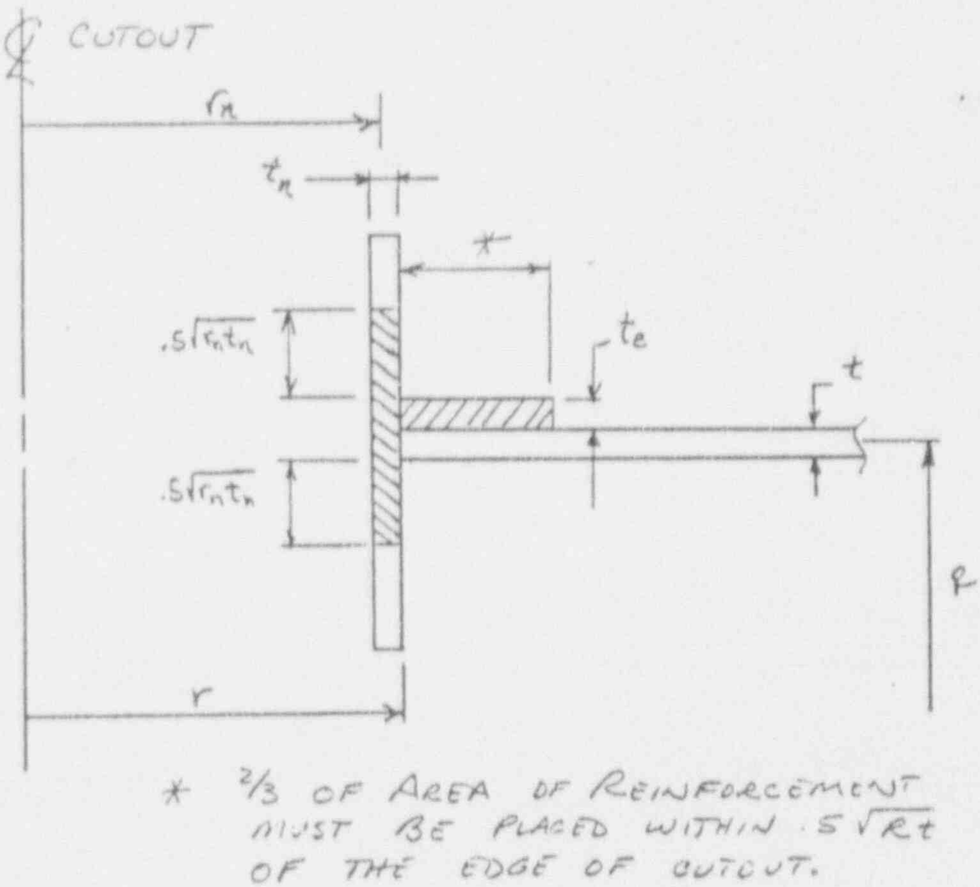
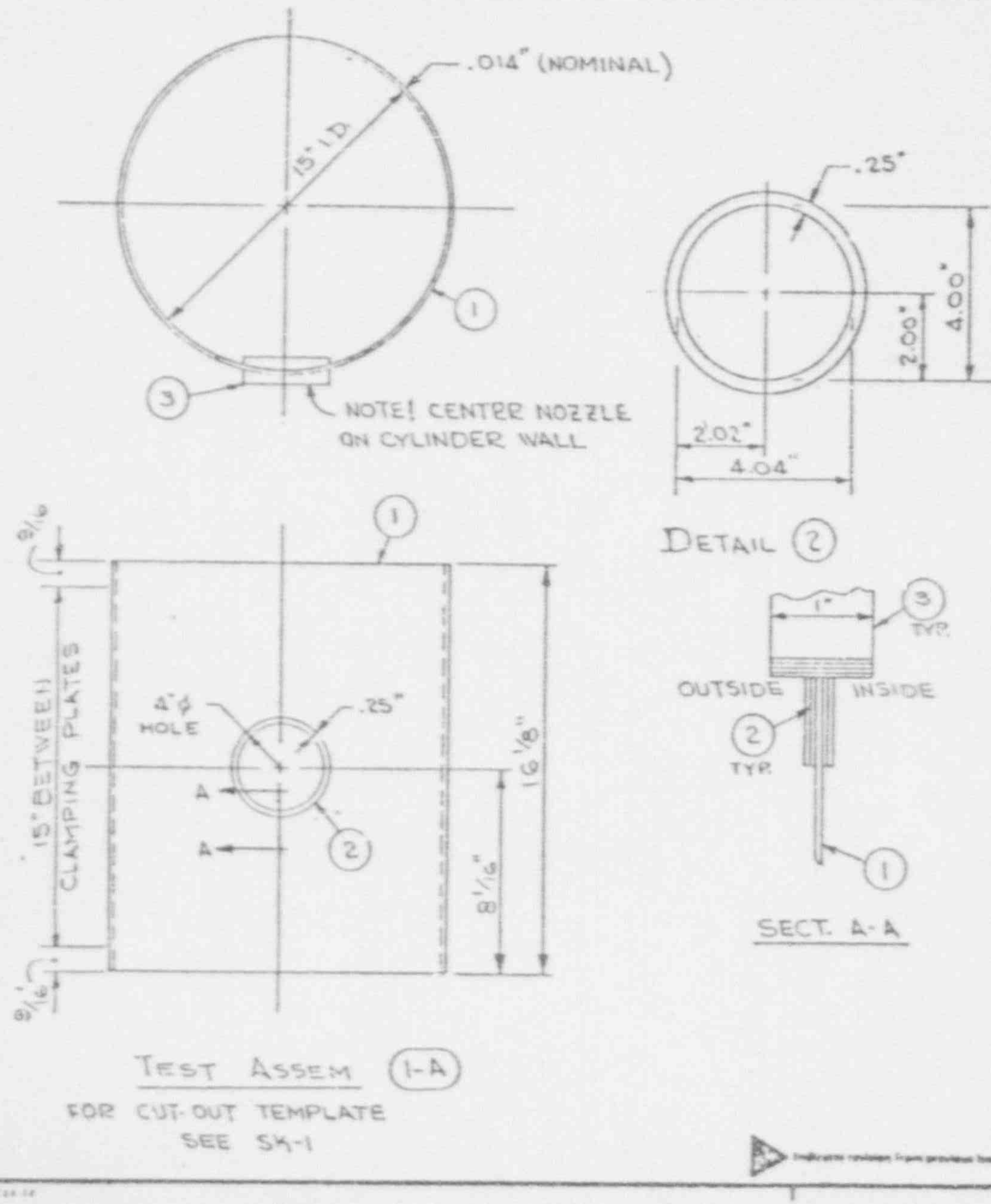


FIG. 2 - LIMITS OF REINFORCEMENT



Ship Pc	Mark	Assm Pc	Description	Length Ft	Length In	Spec
1	1-A		TEST ASSEMBLY			
	1-1	1	15" I.D. x .014 W.T. CYL	1	4 1/8	.014 MYLAR
	1-2	8	REINF. PAD			do
	1-3	4	4"ϕ (NOM) NOZZLE	0	1"	do

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MYLAR TEST CYLINDER

FIGURE 3

Purchaser's No. ____

By JFC Chkd ____ Date 2-26-80

Engineering Coordinator

Contract No. RB 8500

Dwg 1 Rev 0

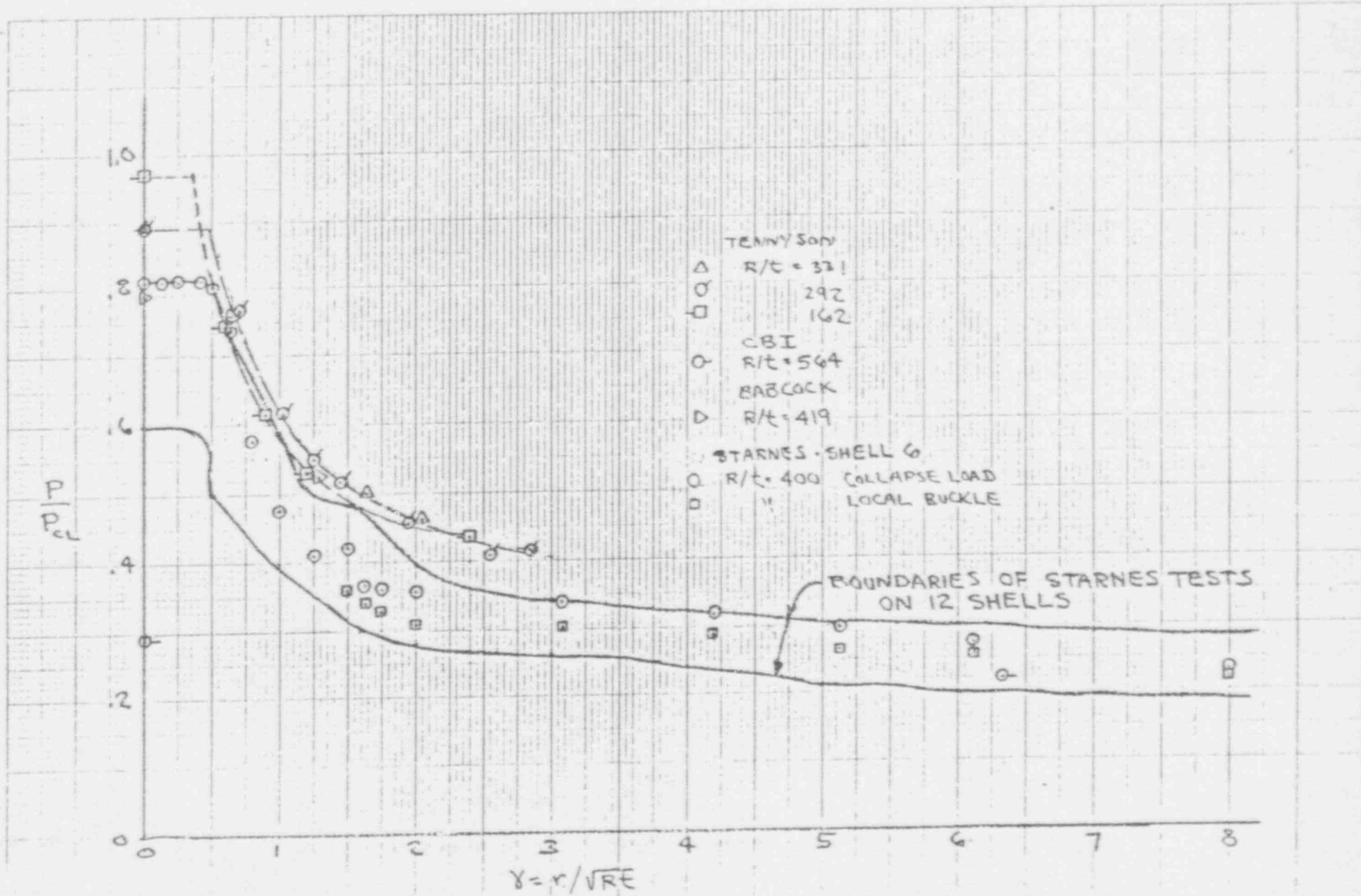


FIG. 4 - BUCKLING OF CYLINDERS WITH UNREINFORCED CIRCULAR OPENINGS

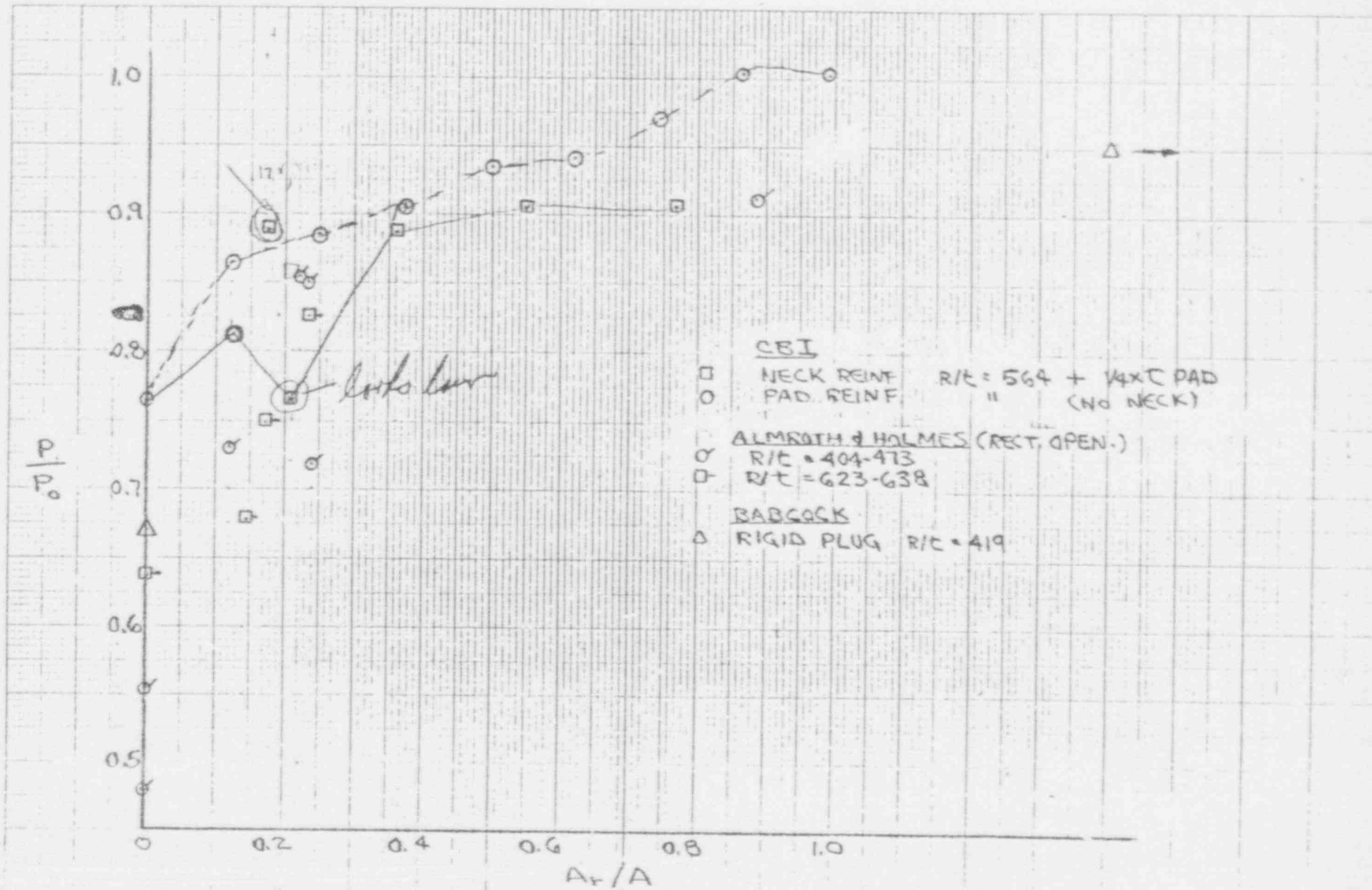
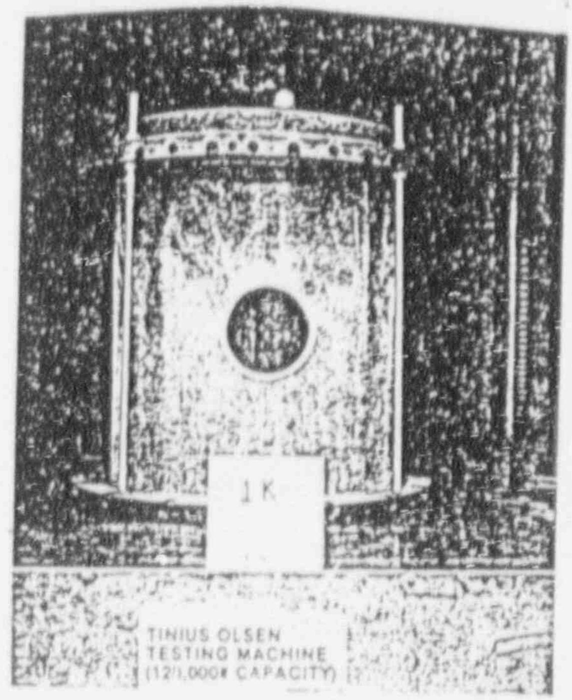
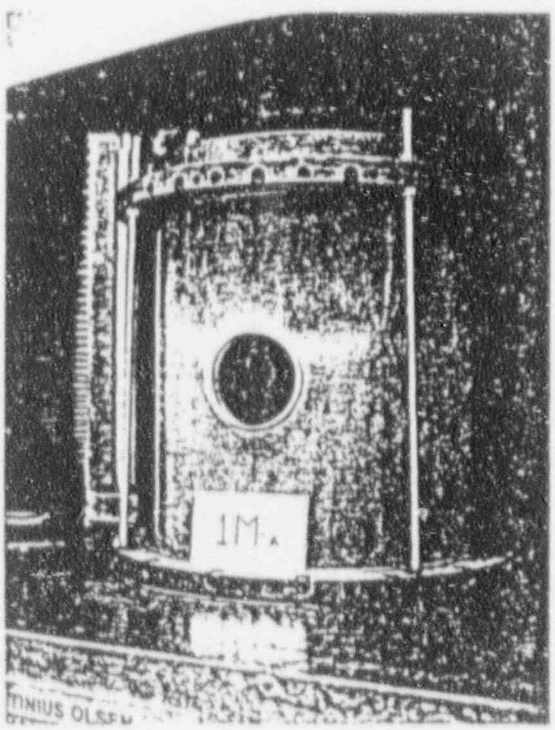


FIG. 5 - BUCKLING OF CYLINDERS WITH REINFORCED OPENINGS

(a) Test 1J ($A_r/A=0.99$)



(b) Test 1K ($A_r/A=0.125$)

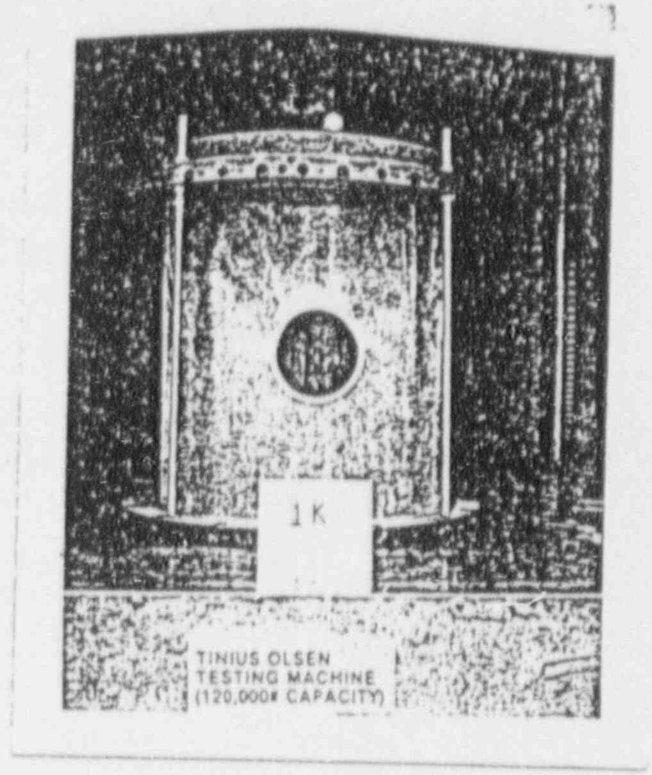


(c) Test 1M-A ($A_r/A=0.350$)

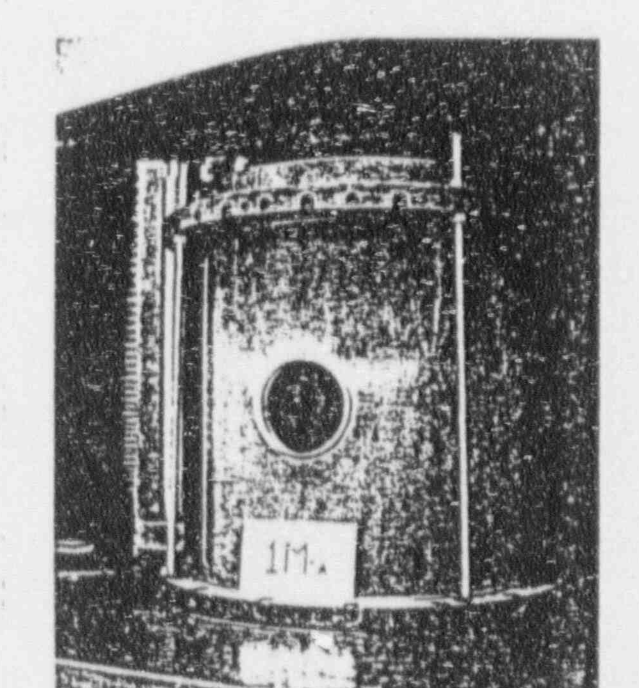
(d) Test 10 ($A_r/A=0.742$)

FIG. 6 - BUCKLED CYLINDERS

(a) Test 1J ($A_r/A=0.99$)



(b) Test 1K ($A_r/A=0.125$)



(c) Test 1M-A ($A_r/A=0.350$)

(d) Test 10 ($A_r/A=0.742$)

FIG. 6 - BUCKLED CYLINDERS