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MEMORANDUM REPORT NO. 1394
MARCH 1962

AN OMNI-DIRECTIONAL GAGE FOR
MEASURING THE DYNAMIC PRESSURE BEHIND A SHOCK FRONT

O. T. Johnson
W. O. Ewing, Jr.



Department of the Army Project No. 503-04-002
Ordnance Management Structure Code No. 5010.11.815
BALLISTIC RESEARCH LABORATORIES



ABERDEEN PROVING GROUND, MARYLAND

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BALLISTIC RESEARCH LABORATORIES

MEMORANDUM REPORT NO. 1394

OTJohnson/WOEwingJr/iv
Aberdeen Proving Ground, Md.
March 1962

AN OMNI-DIRECTIONAL GAGE FOR MEASURING
THE DYNAMIC PRESSURE BEHIND
A SHOCK FRONT

ABSTRACT

The design of a cantilever gage for determining the direction of flow and time history of dynamic pressure is described, along with the results of both static and shock tube calibration.

NOMENCLATURE

Blast Wave Parameters

Q_s	peak dynamic pressure
P_s	side-on peak overpressure
P_o	ambient pressure
y	P_s/P_o
C_D	drag coefficient

Beam Response Parameters

$y_s(x)$	static deflection under uniform pressure
x	distance from clamped end to center of strain gage
r_o	outside radius of beam (of circular cross-section)
r_i	inside radius of beam
θ	angle formed by the line connecting strain gages (180° apart) and the direction of the blast.
B	$2 r_o$
C	$r_i \cos \theta$
$e_s(x)$	static bending strain under uniform pressure
E	Young's modulus
I	Cross-sectional moment of inertia
l	length of cylinder
f_1	fundamental frequency
A	cylinder cross sectional area
λ_1	root of the frequency equation
ρ	density of beam material

INTRODUCTION

The destructive effect of a blast wave emanating from the detonation of a high explosive (HE) charge is often associated with the magnitudes of peak pressure and impulse impinging upon the target. As the explosive weights considered become increasingly large, it is noted that for targets reacting to the effects of crushing by blast the damage becomes more closely related with the peak overpressure. However, for other targets (so-called "drag-type" targets), the effect of dynamic pressure may be of equal importance.

Dynamic pressure is a function of the velocity and density of the air behind the shock front. For classical blast waves and, if we restrict ourselves to air behaving as an ideal gas, then the maximum dynamic pressure, which occurs immediately behind the front, is given by ^{1*}

$$Q_s = P_s \left(2.5 - \frac{17.5}{\gamma + 7} \right) . \quad (1)$$

The dynamic pressure decays from its peak value somewhat more rapidly than the overpressure, and lasts for a longer time.²

Numerous techniques and instruments have been devised, and successfully employed, for measuring the time history of dynamic pressure.³ However, in many of the past experiments, the direction of travel of the shock front was known so that the gages could be properly oriented prior to the experiment.

Recently the problem arose as to how to measure dynamic pressure when the direction of travel of the blast wave could not be determined exactly. It was suggested by C. Kingery of these Laboratories that a suitably instrumented cantilever cylinder could be used to measure both direction and time history of dynamic pressure. We have designed such a gage and will, in this report, describe it and discuss its fabrication, techniques of calibration, and the results of the calibrations.

* Superscripts refer to references.

THEORY

It has been shown by Baker et al.⁴ that there is a correlation between the dynamic response and the "quasi-static" response of a stiff cantilever beam to pressure pulses of long duration*. They showed that the time-histories of bending strain predicted from the Bernoulli-Euler beam equation oscillated about a mean which could be predicted from simple beam theory (which neglects the effect of inertia) for static loading. In addition, they indicated that the drag loading inferred from side-on pressure measurements and steady-state wind tunnel tests agreed with that predicted from the beam response. For our development, we will use response to static loading, keeping in mind that the predicted response will correspond to the mean of the vibratory strain records obtained under blast loading.

Consider a hollow cylindrical tube cantilever mounted vertically and subjected to a dynamic pressure $Q(t)$ which is assumed uniform along its length. The static deflection curve of the tube under uniform transverse pressure, P can be expressed by⁵.

$$y_s(x) = \frac{1}{24} \left[\frac{PB}{EI} \right] x^2 (6l^2 - 4lx + x^2) \quad (2)$$

The bending strain of an outer fiber is then

$$e_s(x) = C \frac{\partial^2 y}{\partial x^2}$$

$$\text{where } \frac{\partial^2 y}{\partial x^2} = \frac{PB}{2EI} (l^2 - 2lx + x^2) \quad (3)$$

$$\text{and } B = 2 r_o$$

$$\text{and } C = r_1 \cos \theta$$

* Of the order of ten times the fundamental period of vibration of the cantilever.

$$\text{Therefore } e_s(x) = \frac{r_1 \cos \theta P_D r_o}{EI} (l^2 - 2lx + x^2) \quad (4)$$

where P_D is the drag pressure.

Now it is necessary that the fundamental period of the cylinder be considerably less than the duration of the blast wave. If durations of the order of 20 ms minimum are assumed, then the fundamental period T_1 should be about 2 ms, yielding a fundamental frequency f_1 of 500 cps.

Consider the design of two gages, one with a fundamental frequency of 1000 cps and the other of 500 cps.

The frequency can be expressed as

$$f_1 = \frac{1}{2\pi} \left(\frac{\lambda_1}{l} \right)^2 \sqrt{\frac{EI}{\rho A}}$$

where $\lambda_1 = 1.875$ for cantilevers.⁶ For aluminum tubing with an outside diameter of 2.250" and inside diameter of 2.00", the lengths to satisfy the fundamental frequency requirement will be 12.9" for 500 cps and 9.10" for 1 KC.

To minimize response to vibration in higher modes, strain gage patches should be placed at the location for zero bending strain in the second mode of vibration, i.e., $x/l = 0.217$ ". However, if the strain patches are placed nearer the root, one can increase the response to the fundamental mode. The second mode of vibration will be apparent when recording but not of sufficient magnitude to be objectionable. Therefore, let us locate the strain patches as close to the root as possible, i.e., $x/l = .083$.

The measured strain can then be used to predict the drag pressure from equation (4). Then the dynamic pressure can be determined from the relation

$$P_D = C_D Q$$

where $C_D = 1.2$ for a cylinder subjected to subsonic flow. Peak dynamic pressure is related to peak side-on pressure as expressed in equation 1. The direction of the loading can be determined by the proper orientation of the strain patches and by the polarity of the record.

In order to check the linearity of the strain response at various yaw angles, the gage can be subjected to a concentrated transverse load W at its free end. The deflection can then be expressed as⁷

$$y = -\frac{1}{6} \frac{W}{EI} (3lx^2 - x^3).$$

$$\text{then } \frac{\partial y}{\partial x} = -\frac{1}{6} \frac{W}{EI} (6lx - 3x^2),$$

$$\text{and } \frac{\partial^2 y}{\partial x^2} = -\frac{W}{EI} (l - x).$$

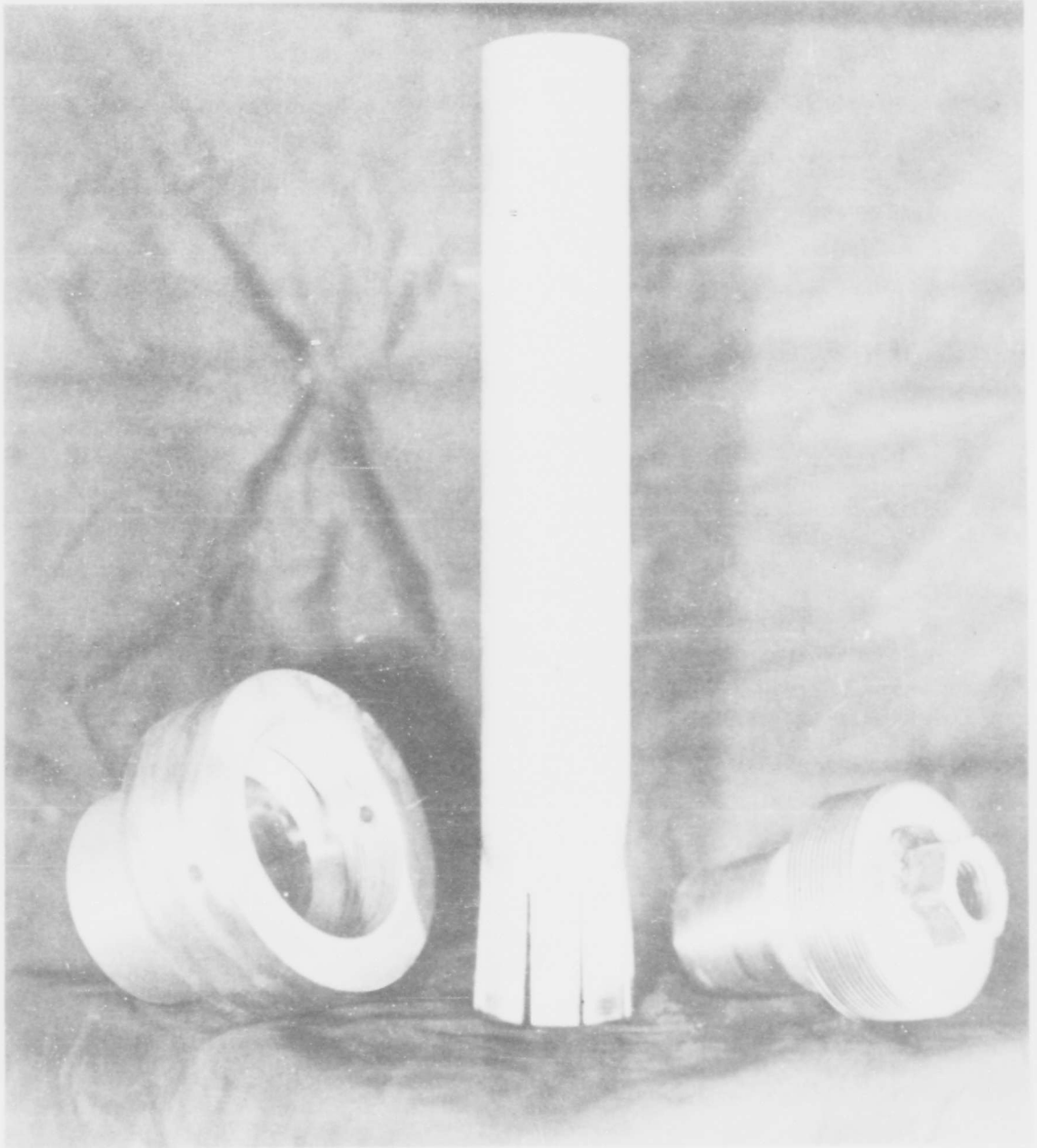
$$\text{Bending strain } e = -c \frac{\partial^2 y}{\partial x^2} = \frac{CW}{EI} (l - x) = \frac{r_1 \cos \theta W}{EI} (l - x) \quad (5)$$

Static end loadings of the cylinder should yield results agreeing with above formulation.

DESCRIPTION OF GAGE

The gage is an aluminum cylinder capped at one end, and instrumented near the base with four strain patches (where $x/l = .083$) affixed at 90° intervals around the inner surface of the cylinder and oriented to measure longitudinal strain. This assembly is securely mounted in a sturdy base. The clamped end is slit longitudinally at several locations about the cylinder circumference, with the slits extending from the base end of the cylinder to a point just below the effective length of the gage (Figure 1). The slits are to facilitate firm positioning, and to prevent cocking of the cylinder when pressures are applied. The cylinder is then inserted into the smaller end of a tapered hole through a base plate, until the slits are just below the

FIGURE 1
UNASSEMBLED GAGE



surface. Through the other end of the base plate a tapered plug is threaded. This plug expands the slit end of the cylinder until the outer surface fits tightly against the inner surface gripping the plug tightly. The plug is center drilled to permit exit of the strain gage leads. The mount described was designed for use in a shock tube. A slight modification would be necessary to adapt the assembly for field trials. Two gages were fabricated; one for each fundamental frequency considered.

STATIC CALIBRATION

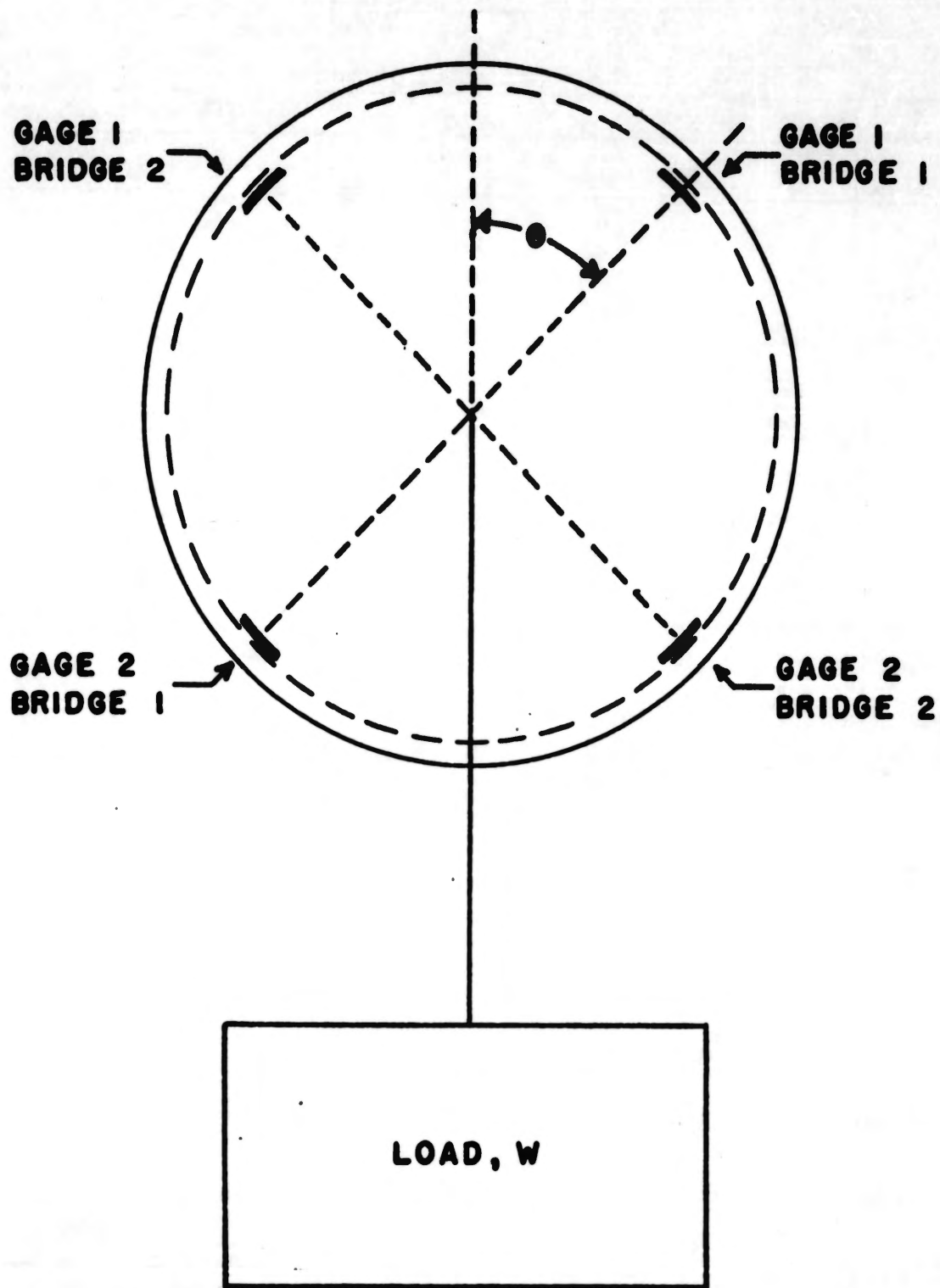
Static calibration of the gages was accomplished by mounting them as indicated in Figure 2 and applying loads at the capped end, with the resultant strains being read from a Baldwin SR4 Type M Strain Indicator. Readings were recorded as the weights were added, again as they were being removed, for various values of angle θ between line of action of the force and strain gage location. The average value of the two observations appear in Table I.

SHOCK TUBE TRIALS

Trials were conducted in the 24-inch shock tube with both omnidirectional gages. The gages were subjected to nominal side-on overpressures of 10 psi and 30 psi at orientations, (θ 's) of 0° , 30° , 45° , and 60° . The results of these investigations will be presented in later sections of this report.

RESULTS AND DISCUSSION

Table I indicates the results of static application of end loads to the cantilever-mounted cylinders. Figures 3 and 4 display representative plots of force vs. strain obtained by the calibration and compared to the values calculated from equation 5. The agreement appears good enough to justify use of equation 4 to describe the gage response.



STATIC CALIBRATION

FIGURE 2

TABLE I

Indicated Strains from Forces Applied
at Several Angular Orientations
with Respect to the Strain Patches

Average Indicated Strain*, μ ins/in

Gage Orientation →	Strain Patches 1 and 3					Strain Patches 2 and 4				
	0°	30°	45°	60°	90°	0°	30°	45°	60°	90°
	9.10"					Gage Assembly				
Force, lbs.										
10.1	39	35	23	19	3	35	35	22	20	1
20.3	77	69	53	38	2	73	71	57	42	4
30.6	123	102	81	52	3	117	97	84	63	3
40.8	161	136	109	75	4	157	140	116	84	12
51.0	200	170	137	94	4	195	185	144	104	13
61.1	238	202	163	111	5	233	207	171	123	15
71.4	276	236	189	128	5	270	239	197	143	16
Calculated Strain for										
71.4 lbs.	244	212	173	122	0	244	212	173	122	0
	12.9"					Gage Assembly				
Force, lbs.										
10.1	47	39	34	22	3	51	43	36	26	3
20.3	95	84	67	47	4	103	89	73	52	4
30.6	143	129	99	69	7	154	134	111	76	6
40.8	191	166	133	90	9	207	183	147	104	7
51	241	206	167	113	9	258	225	184	129	11
Calculated Strain for										
51 lbs.	248	214	175	124	0	248	214	175	124	0

* Twice the actual strain

Figure 3
ACTUAL BENDING STRAIN OF ALUMINIUM CYLINDER
WITH 500 CPS FUNDAMENTAL FREQUENCY
(STATIC LOAD, $\theta = 0^\circ$)

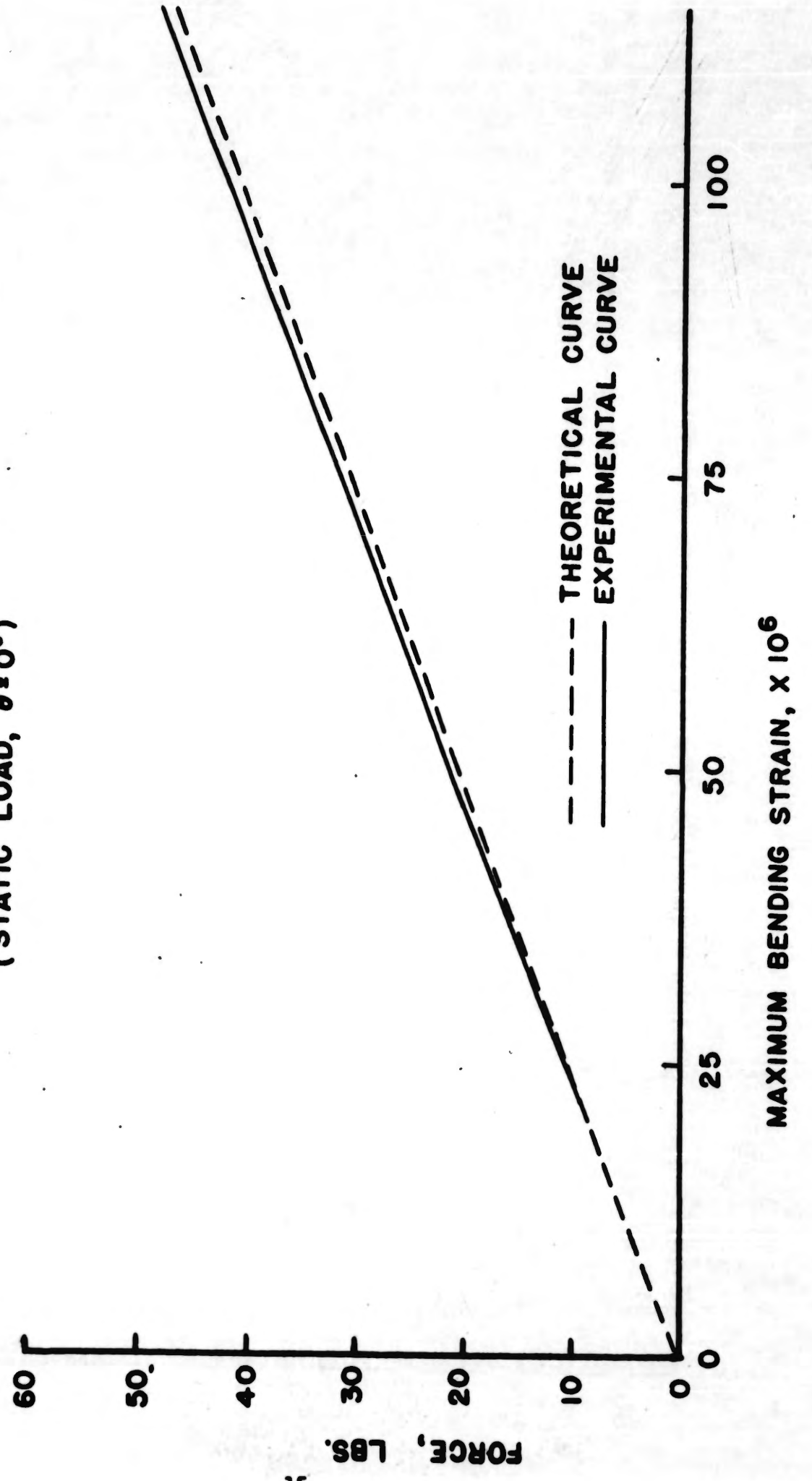
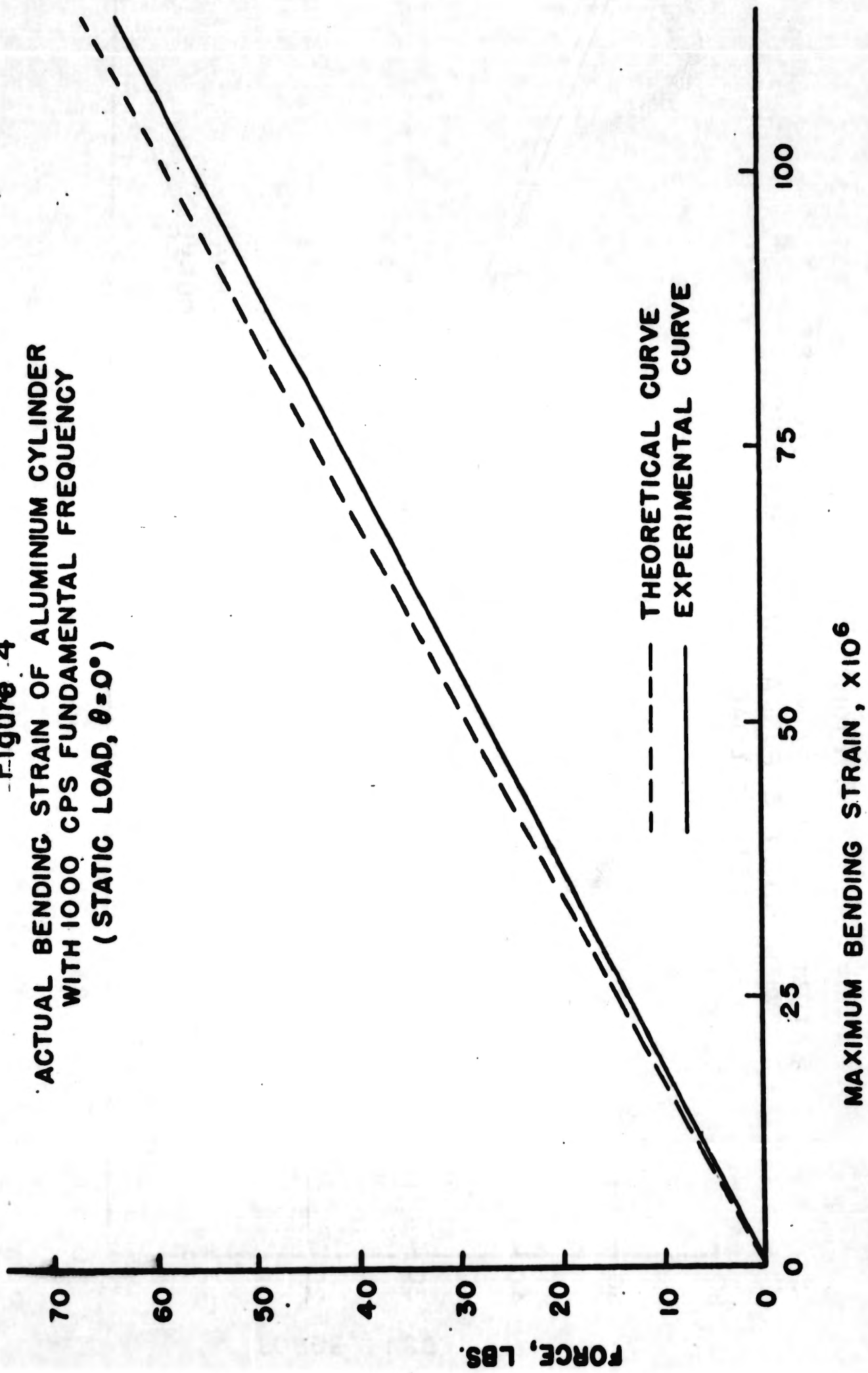


Figure 4

ACTUAL BENDING STRAIN OF ALUMINIUM CYLINDER
WITH 1000 CPS FUNDAMENTAL FREQUENCY
(STATIC LOAD, $\theta=0^\circ$)



The strain-time histories recorded when the cylinders were subjected to shock tube loading clearly indicated the oscillation about a mean discussed previously. Some initial difficulty was experienced in interpreting the peak strain due to the rounding off of the trace after the initial rise especially at the lower values of θ or higher bending strains. However, examination of methods to determine the peak indicated that the intersection obtained by extrapolating the rise time and the mean of the decay curve provided the best estimate.

Table II is a tabulation of the calculated and recorded strains for the two pressure levels that were considered in the shock tube. Figures 5 through 12 are graphical presentations indicating the agreement of the measured strain with the predicted for the pressures and strain gage orientations (θ) considered. The measured strains agree reasonably well with the predicted thus indicating rather accurate estimates of the peak dynamic pressure.

A comparison of the strain-time traces with the pressure-time traces (Figure 13) indicates that the strain duration is longer than the pressure-time which agrees with previous observations. It is also noted that the initial decay of the strain trace is much more rapid than the pressure trace. However, it was impossible to accurately determine the strain-time duration.

CONCLUSION

From the previous discussion it is apparent that the omni-directional gage is practical and does have application in several aspects of blast instrumentation. It is important however, that thought be directed toward proper design of the mount to prevent slippage and to selection of the cylinder dimensions to obtain the proper response while retaining sufficient strength to prevent crushing damage and bending at the root.

O. T. Johnson

O. T. JOHNSON

W. O. Ewing

W. O. EWING, JR.

TABLE II

Comparison of Calculated and Recorded
Strains for Two Pressure Levels

Pressure, psi	Long Beam (500 cps)				Short Beam (1000 cps)			
	Strain, X 10 ⁶				Strain, X 10 ⁶			
	Calculated	Recorded		Calculated	Recorded			
		No. 1 Bridge	No. 2 Bridge		No. 1 Bridge	No. 2 Bridge		
		<u>0°</u>			<u>0°</u>			
30	631	506	669	314	313	397		
10	83	121	67	41	41	75		
		<u>30°</u>			<u>30°</u>			
30	597	418	353	272	281	202		
10	72	105	67	39	40	70		
		<u>45°</u>			<u>45°</u>			
30	446	489	380	222	218	250		
10	59	97	56	29	57	41		
		<u>60°</u>			<u>60°</u>			
30	316	295	418	157	202	157		
10	42	56	44	21	43	33		

FIGURE 5
MAXIMUM BENDING STRAIN OF ALUMINIUM CYLINDER
WITH 500 CPS FUNDAMENTAL FREQUENCY
($\theta = 0^\circ$)

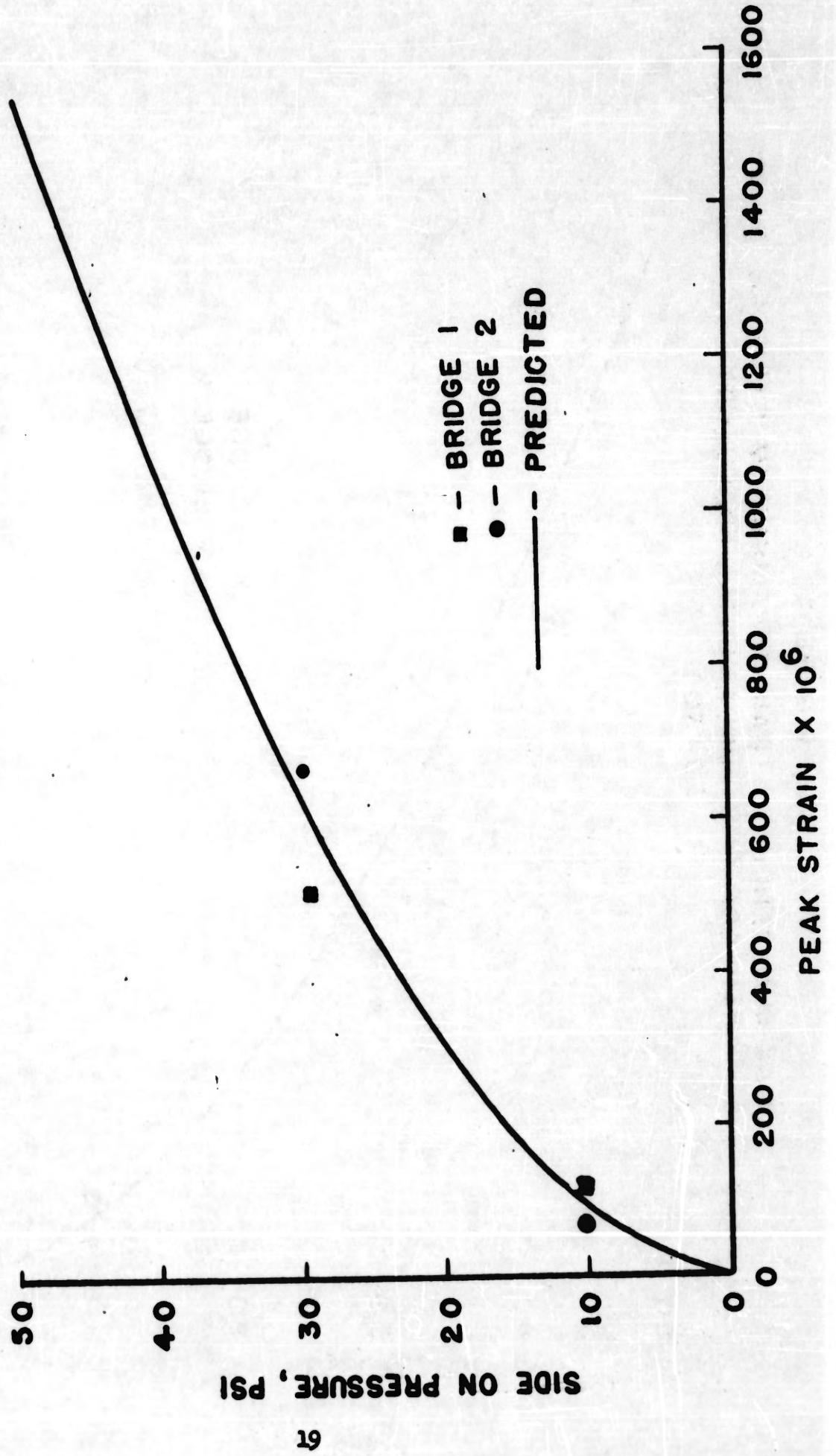


FIGURE 6
MAXIMUM BENDING STRAIN OF ALUMINIUM CYLINDER
WITH 500 CPS FUNDAMENTAL FREQUENCY
($\theta = 30^\circ$)

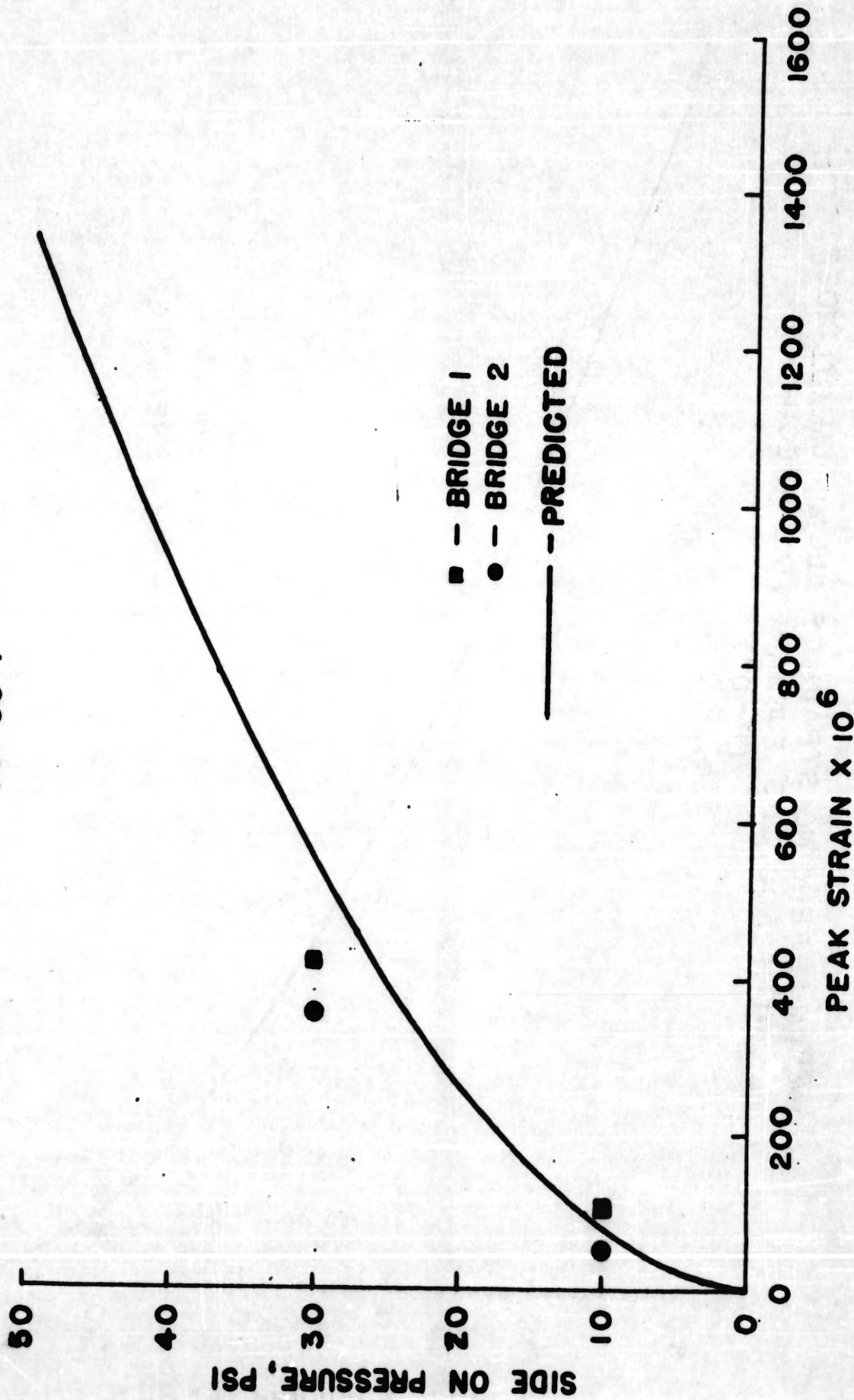


FIGURE 7
MAXIMUM BENDING STRAIN OF ALUMINIUM CYLINDER
WITH 500 CPS FUNDAMENTAL FREQUENCY
($\theta = 45^\circ$)

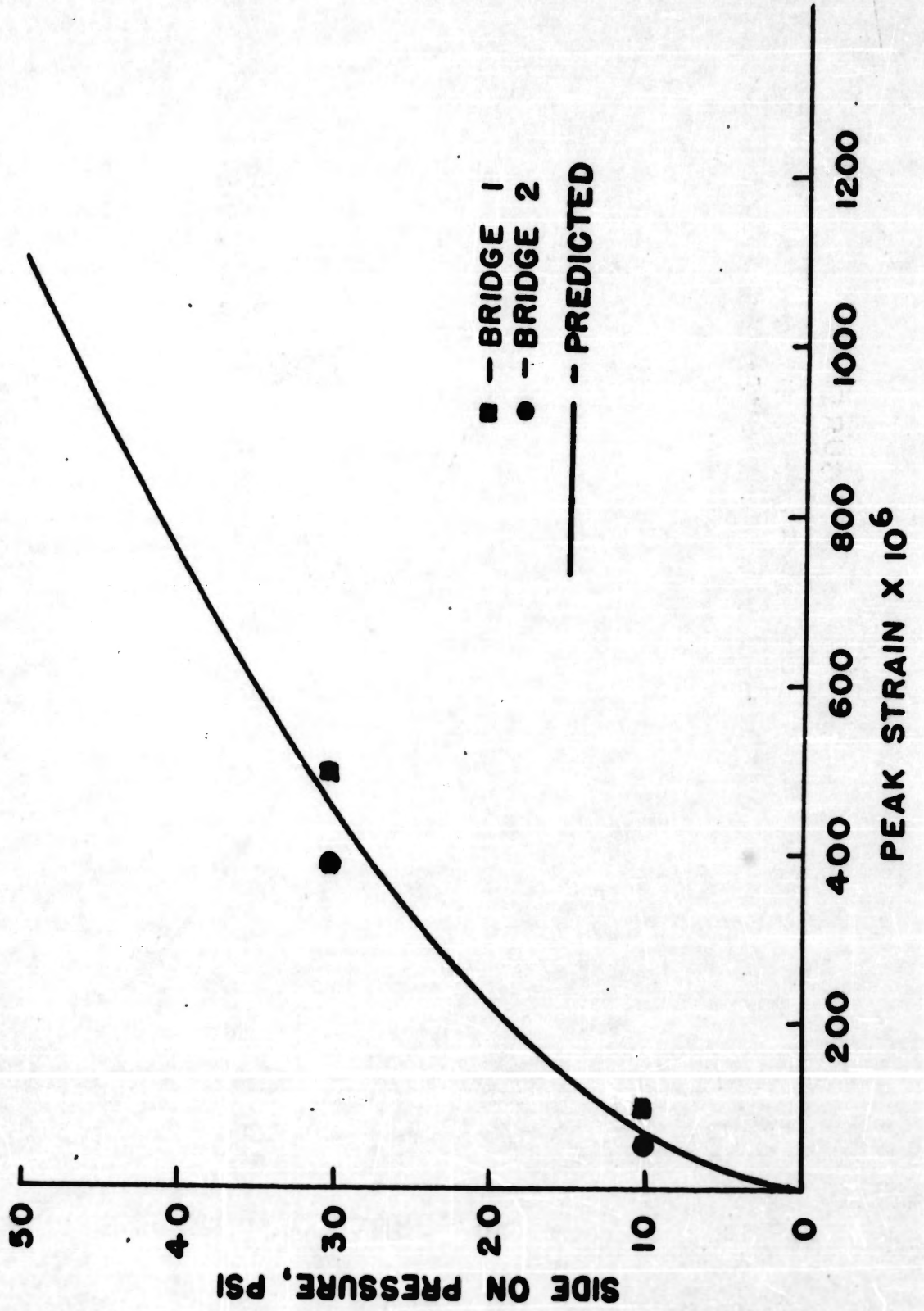


FIGURE 8
MAXIMUM BENDING STRAIN OF ALUMINIUM CYLINDER
WITH 500 CPS FUNDAMENTAL FREQUENCY
 $\theta = 60^\circ$

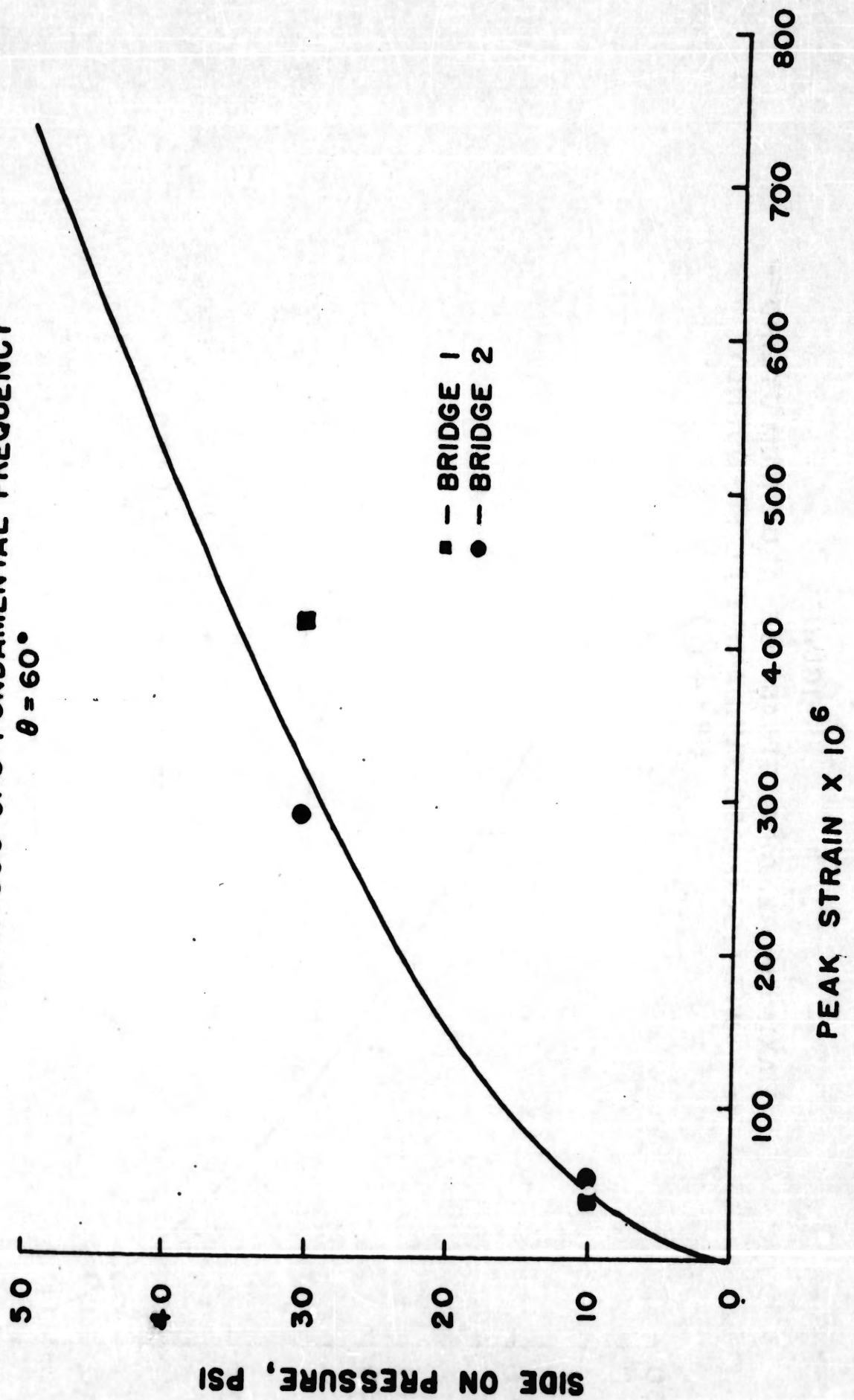


FIGURE 9
MAXIMUM BENDING STRAIN OF ALUMINUM CYLINDER
WITH 1000 CPS FUNDAMENTAL FREQUENCY
($\theta = 0^\circ$)

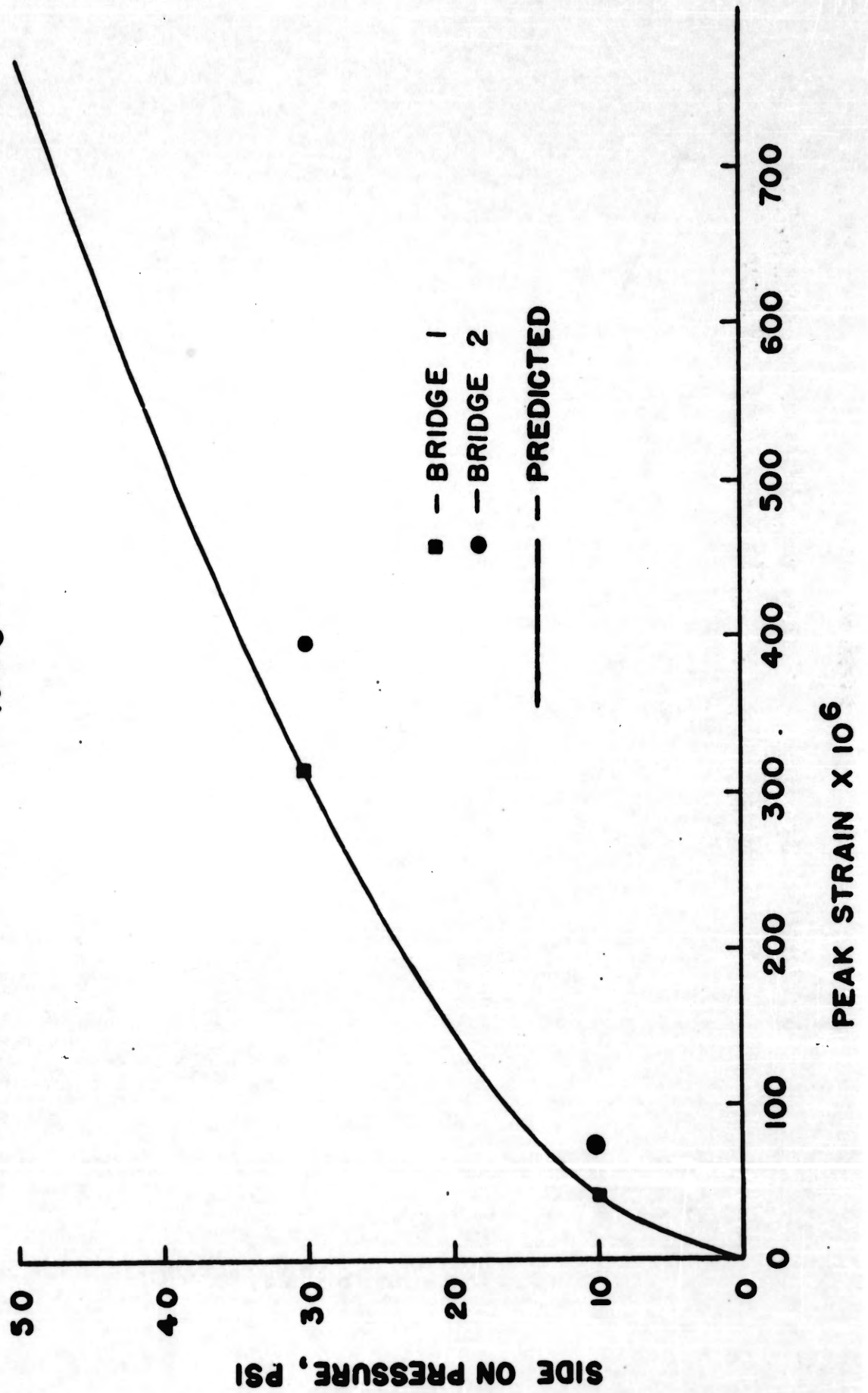


FIGURE 10

MAXIMUM BENDING STRAIN OF ALUMINIUM CYLINDER
WITH 1000 CPS FUNDAMENTAL FREQUENCY
($\theta = 30^\circ$)

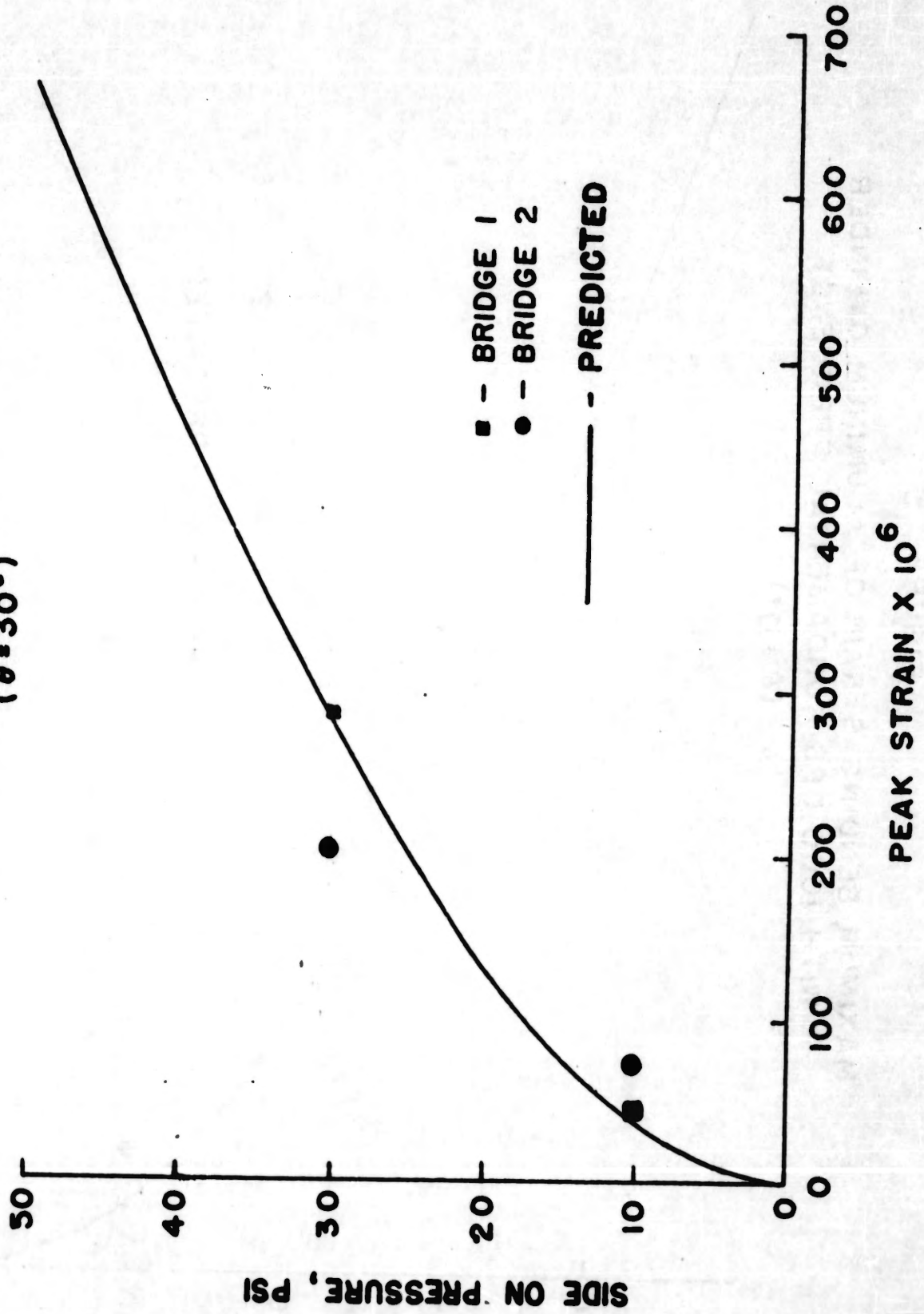


FIGURE II
MAXIMUM BENDING STRAIN OF ALUMINIUM CYLINDER
WITH 1000 GPS FUNDAMENTAL FREQUENCY
($\theta = 45^\circ$)

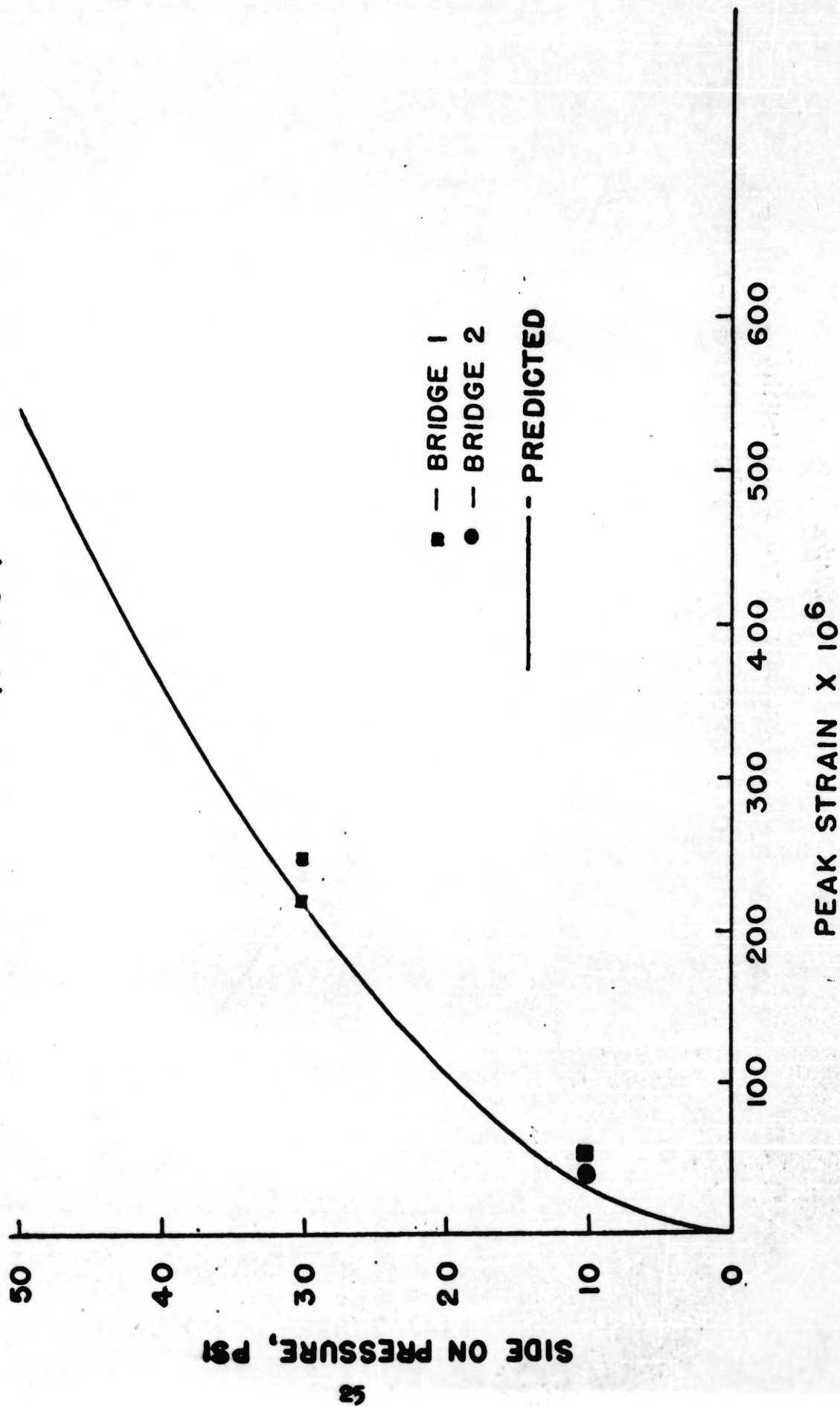


FIGURE 12
MAXIMUM BENDING STRAIN OF ALUMINIUM CYLINDER
WITH 1000 CRS FUNDAMENTAL FREQUENCY
($\theta = 60^\circ$)

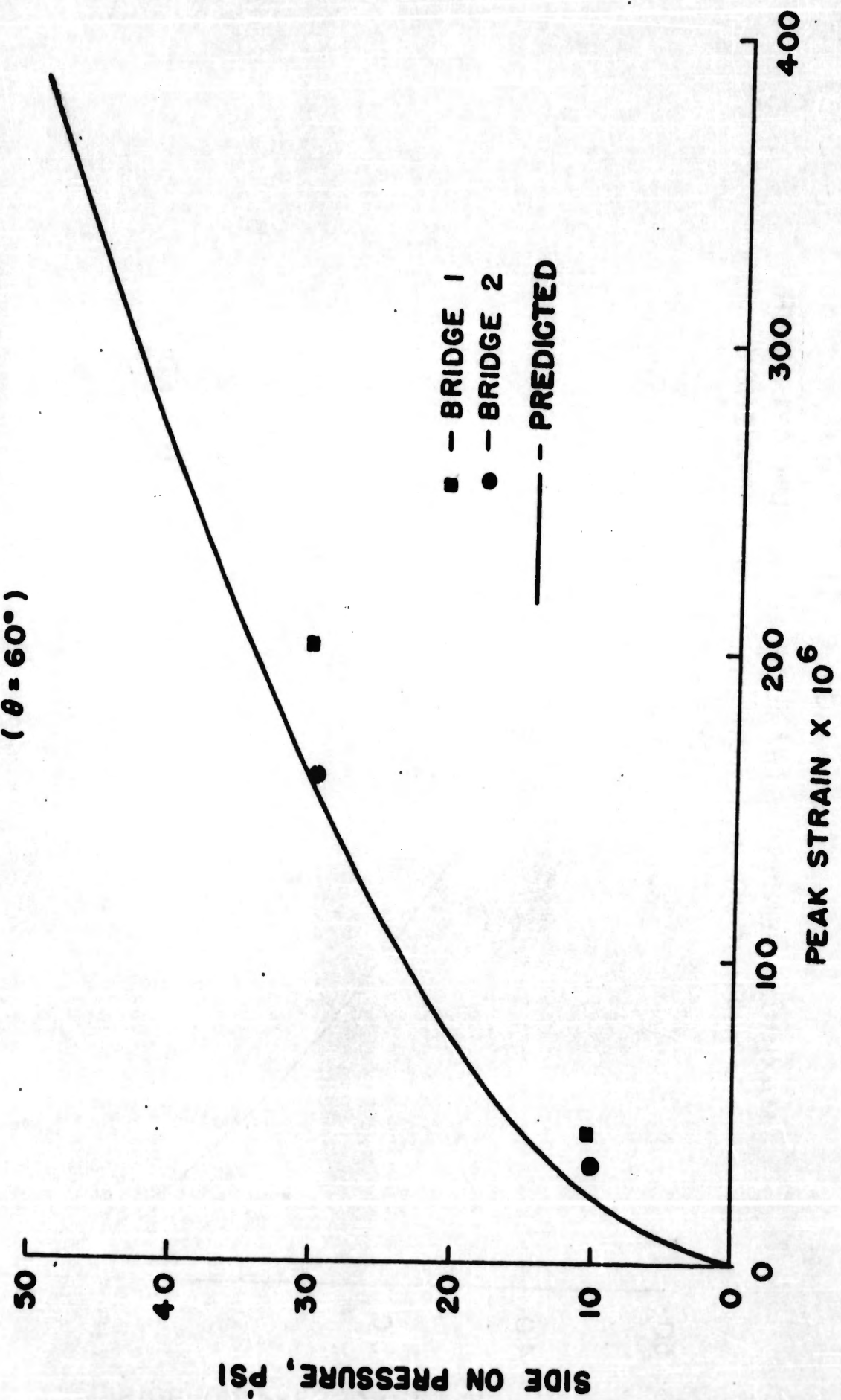
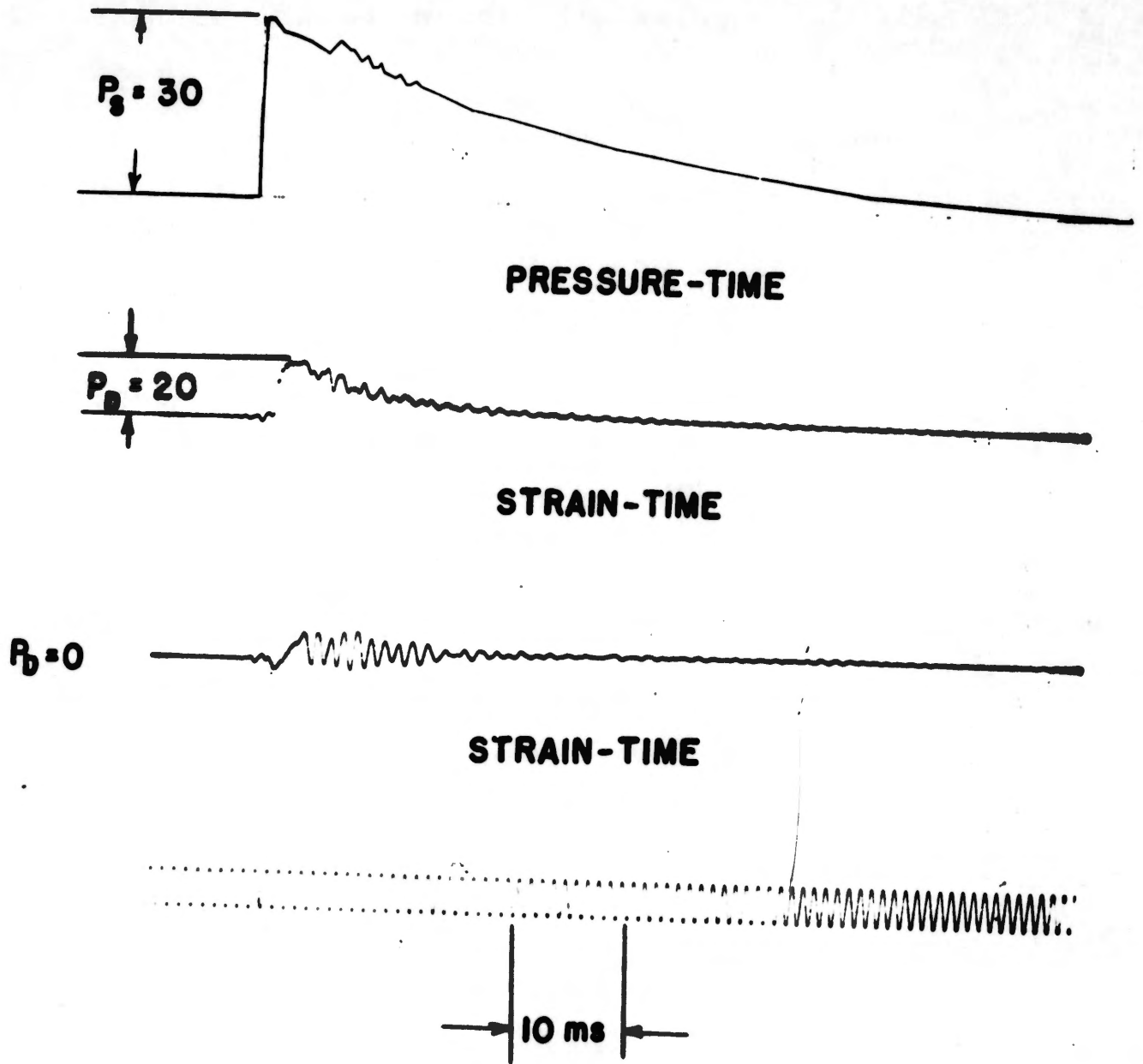


FIGURE 13
COMPARISON OF PRESSURE-TIME AND
STRAIN-TIME TRACES



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4	Defence Research Member Canadian Joint Staff 2450 Massachusetts Avenue, N.W. Washington 8, D.C. Of Interest to: Suffield Experimental Section Ralston Alberta, Canada ATTN: Mr. Trevor Groves Dr. John Dewey

<p>AD Ballistic Research Laboratories, AFG AN OMNI-DIRECTIONAL GAGE FOR MEASURING THE DYNAMIC PRESSURE BEHIND A SHOCK FRONT O. T. Johnson, W. O. Ewing, Jr.</p> <p>ERL Memorandum Report No. 1394 March 1962</p> <p>DA Proj No. 503-04-002, OMSC No. 5010.11.815 UNCLASSIFIED Report</p> <p>The design of a cantilever gage for determining the direction of flow and time history of dynamic pressure is described, along with the results of both static and shock tube calibration.</p>	<p>UNCLASSIFIED</p> <p>Elast effects - Measurement Explosions - Pressure</p> <p>Accession No. Ballistic Research Laboratories, AFG AN OMNI-DIRECTIONAL GAGE FOR MEASURING THE DYNAMIC PRESSURE BEHIND A SHOCK FRONT O. T. Johnson, W. O. Ewing, Jr.</p> <p>ERL Memorandum Report No. 1394 March 1962</p> <p>DA Proj No. 503-04-002, OMSC No. 5010.11.815 UNCLASSIFIED Report</p> <p>The design of a cantilever gage for determining the direction of flow and time history of dynamic pressure is described, along with the results of both static and shock tube calibration.</p>
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