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BENDING-STIFFNESS PROPERTIES OF A PRESTRESSED SEGMENTED CERAMIC PLATE

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ABSTRACT

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This report summarizes the results of an experimental investigation of the structural characteristics of a prestressed segmented ceramic plate. The plate was composed of one-inch-thick square ceramic blocks that were held together by steel wire-ropes. The structural properties of interest were the bending, twisting, and Poisson stiffnesses.

The experimentation involved two cylindrical bending tests for the determination of the flexural stiffnesses D_x and D_y, an anticlastic bending test to find the Poisson stiffness D_1 and two twisting tests to determine the twisting stiffness D_{xy}. The experimental results were as follows: D_x was 28,550 lb-in.^{2}/in., D_y was 13,450 lb-in.^{2}/in., and D_{xy} was 62,000 lb-in.^{2}/in. on the average. D_1 was very small, being 305 lb-in.^{2}/in. These stiffnesses were different at various plate locations because of non-uniformities of the plate prestress.

The stiffness constants D_x, D_y, D_{xy}, and D_1 also were derived analytically from the geometries of the cross section and an effective elastic modulus E and an effective Poisson ratio μ of the composite plate. The flexural stiffnesses D_x and D_y were calculated to be 37,300 lb-in^2/in., and 13,300 lb-in.^{2}/in., respectively, whereas D_{xy} was calculated to be 156,000 lb-in.^{2}/in. The Poisson stiffness D_1 was calculated to be 5,560 lb-in.^{2}/in. The agreement between the experimental and analytical stiffnesses is considered to be good in view of the assumptions involved in the calculations.

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I. INTRODUCTION

The work described in this report is a part of a continuing research program at the University of California, Los Angeles, on structural applications of ceramics (see References 1, 2, 3, 4, 5, 6, 7). The compressive strengths of most ceramics are about ten times greater than their tensile strengths. However, in ceramic structural materials large tensile stresses may be eliminated by prestressing. Prestressing gives the ceramic material an increase in load carrying capacity and gives a marked improvement in the resistance to brittle failure. Other reports on prestressed ceramics and prestressed slabs are given in References 8-13.

As a part of the general research program, an experimental investigation was made of the structural characteristics of a prestressed ceramic plate. The biaxially prestressed plate was composed of square ceramic blocks which were held together by cables. The ceramic blocks were separated by asbestos gasketing for better stress distribution. The cables lying parallel to the x axis were lower than those lying parallel to the y axis. As a result the plate was expected to be orthotropic, i.e., the bending properties should not be the same for both the x and y directions. A rigorous analysis of the segmented plate would require a treatment of the system as a highly redundant structure of discrete elements. Such a treatment would be beyond the scope of this investigation. The approach taken herein is to treat the plate as a homogeneous orthotropic plate and to determine the average bending properties of the whole plate. Then the behavior of the plate under various load conditions can be predicted on the basis of the small deflection theory of plates.

The small deflection theory of orthotropic plates may be found in standard texts, for example, Reference 14, by Timoshenko and Woinowsky-Krieger. The basic expressions of this theory are three second-order differential equations which relate the curvatures and twist of an infinitesimal plate element to the moments acting upon it. The expressions are:

$$M_x = -\left(D_x \frac{\partial^2 w}{\partial x^2} + D_1 \frac{\partial^2 w}{\partial y^2}\right) \qquad (1)$$

$$M_y = -\left(D_y \frac{\partial^2 w}{\partial y^2} + D_1 \frac{\partial^2 w}{\partial x^2}\right) \qquad (2)$$

$$M_{xy} = -2D_{xy} \frac{\partial^2 w}{\partial x \partial y} \qquad (3)$$

The second order differential terms are equal to the plate curvatures:

$$\frac{\partial^2 w}{\partial x^2} = -1/R_x \qquad (4)$$

$$\frac{\partial^2 w}{\partial y^2} = -1/R_y \qquad (5)$$

$$\frac{\partial^2 w}{\partial x \partial y} = -1/R_{xy} \qquad (6)$$

The three differential equations (1), (2), and (3) have four independent constants: two flexural stiffnesses D_x and D_y, a twisting stiffness D_{xy}, and a Poisson stiffness D_1. These constants describe the plate deformation associated with simple loading conditions and may be regarded as fundamental properties of the plate.

The object of this research was to determine the four stiffness constants for a prestressed segmented ceramic plate. This was to be accomplished by conducting 1) cylindrical bending tests in the x and y directions, 2) an anticlastic bending test in the x direction, and 3) a twisting test.

The cylindrical bending tests were made to obtain the flexural stiffnesses D_x and D_y. Cylindrical bending causes a curvature about the primary axis of bending and allows no curvature about the secondary axis. In this case, the flexural stiffnesses become the ratios of bending moment to primary curvature, as may be seen from Equations (1) and (2). Thus, for cylindrical bending about the y axis $\frac{1}{R_y} = 0$, and

$$D_x = \frac{M_x}{1/R_x} \tag{7}$$

and for cylindrical bending about the x axis $\frac{1}{R_x} = 0$, and

$$D_y = \frac{M_y}{1/R_y} \tag{8}$$

The anticlastic bending test was made to obtain the Poisson stiffness D_1. In this test the plate is permitted to bend about the secondary axis while being forced to bend about a primary axis. In the experimental evaluation of stiffnesses the x axis was taken as the primary axis. The Poisson stiffness D_1 as derived from Equation (2) with $M_y = 0$, is:

$$D_1 = -D_y \frac{1/R_y}{1/R_x} \tag{9}$$

The stiffness D_1 can also be computed from Equation (7), with the following result:

$$D_1 = \frac{1}{1/R_y} \left(M_x - D_x \, 1/R_x \right) \tag{10}$$

However, if the curvature in the y direction is small, this is a less accurate measure of D_1 than in Equation (9). This is an important consideration in evaluating the experimental results.

The twisting test was made to find the twisting stiffness D_{xy}. In this test, a pure twist is imposed on the plate by applying four equal vertical forces at the corners of the plate. Two diagonally opposite forces acted upwards while the other two acted downwards. From Equation (3) the twisting stiffness is

$$D_{xy} = \frac{M_{xy}}{2\left(1/R_{xy}\right)} \tag{11}$$

II. EXPERIMENTAL PROGRAM

a. Description of the Prestressed Segmented Ceramic Plate

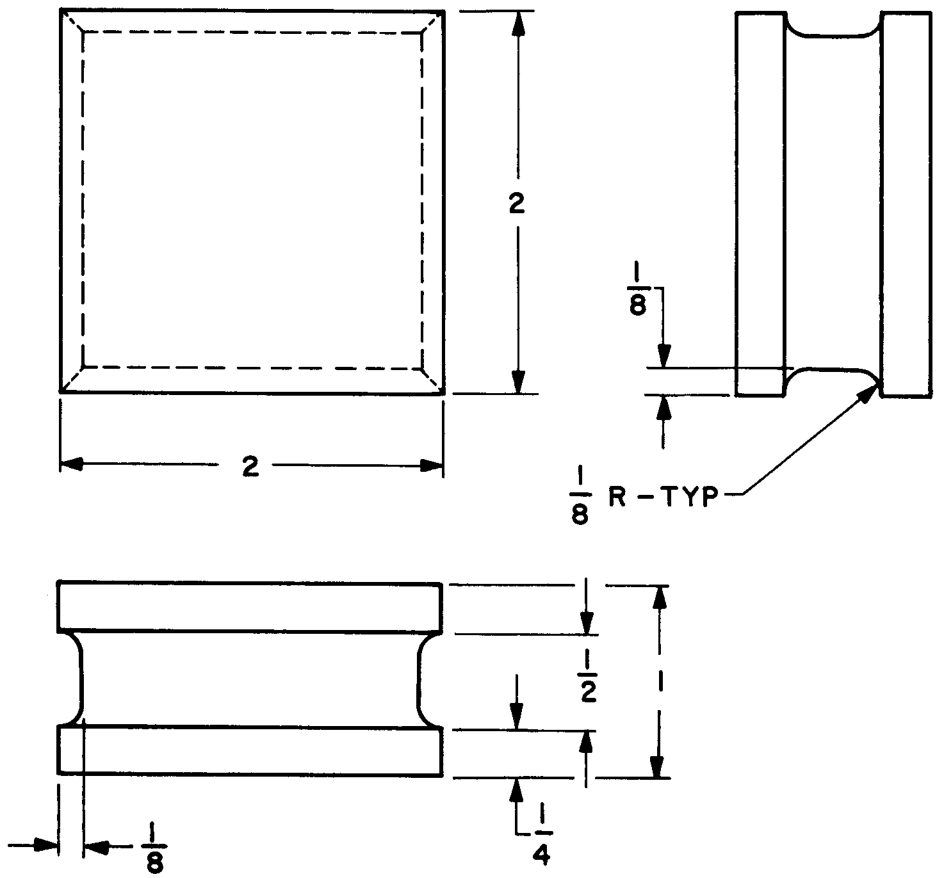
The prestressed plate was comprised of 529 separate 2" x 2" square 1" thick ceramic blocks which were held together by 3/16" 7 x 19 strand steel wire-rope cables. The blocks were formed by extrusion of a ceramic body normally used for the manufacture of sewer pipe. The mechanical properties of the ceramic material are given below (see Reference 15). Figure 1 shows the dimensions of the blocks. Photographs of the plate in construction are given in Figures 2 and 3. All bearing surfaces of the ceramic blocks were separated by a 1/16" thickness of rubber impregnated asbestos sheets (Garlock 900). A 1" x 1/4" steel bar was placed on all four edges of the plate to anchor the cables and to distribute the stress on the ceramic. This steel bar was cut between every other wire after the plate was assembled. The overall dimensions of the plate were 49" x 49" x 1", with 23 blocks on each side.

MECHANICAL PROPERTIES OF THE
CERAMIC MATERIAL

Density	0.085 lb/in.^{3}
Apparent Porosity	5.3%
Absorption (water)	2.2%
Modulus of Elasticity	5.4 x 10^6 psi
Ultimate Compressive Strength	12,000 psi

b. Plate Prestress

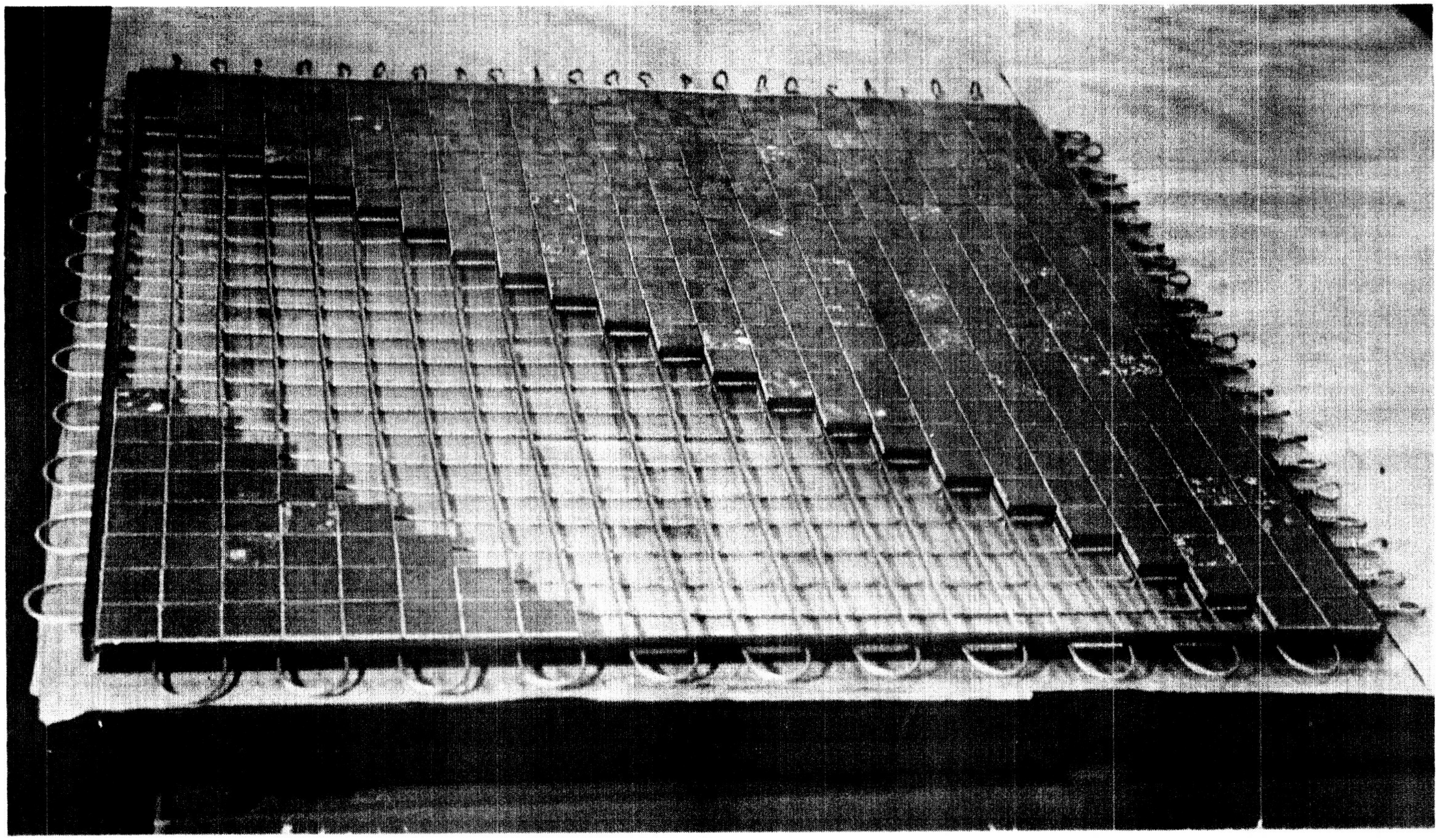
The biaxial prestress of the ceramic plate was adjusted with a prestressing fixture, as shown in Figure 4. The prestressing fixture was a frame which simultaneously pulled on alternate sets of cables and pushed against the steel bar. In this manner the cables were tensioned and the ceramic blocks were compressed. Twelve cables, on one side of the plate, were stressed all at the same time. The remaining cables were stressed in the same manner until the entire plate was biaxially prestressed.



SCALE: FULL SIZE

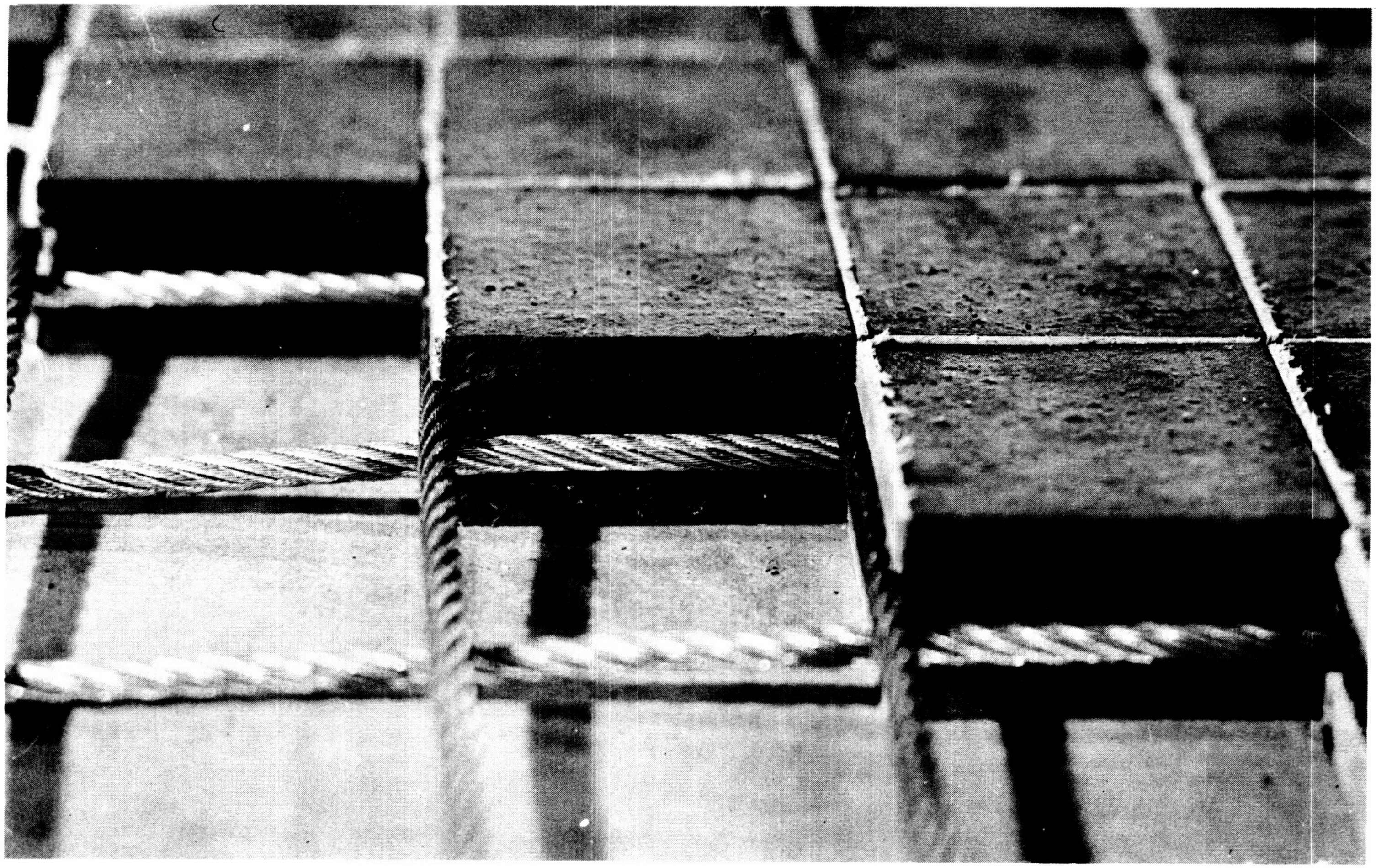
CERAMIC BLOCK DIMENSIONS

FIGURE 1



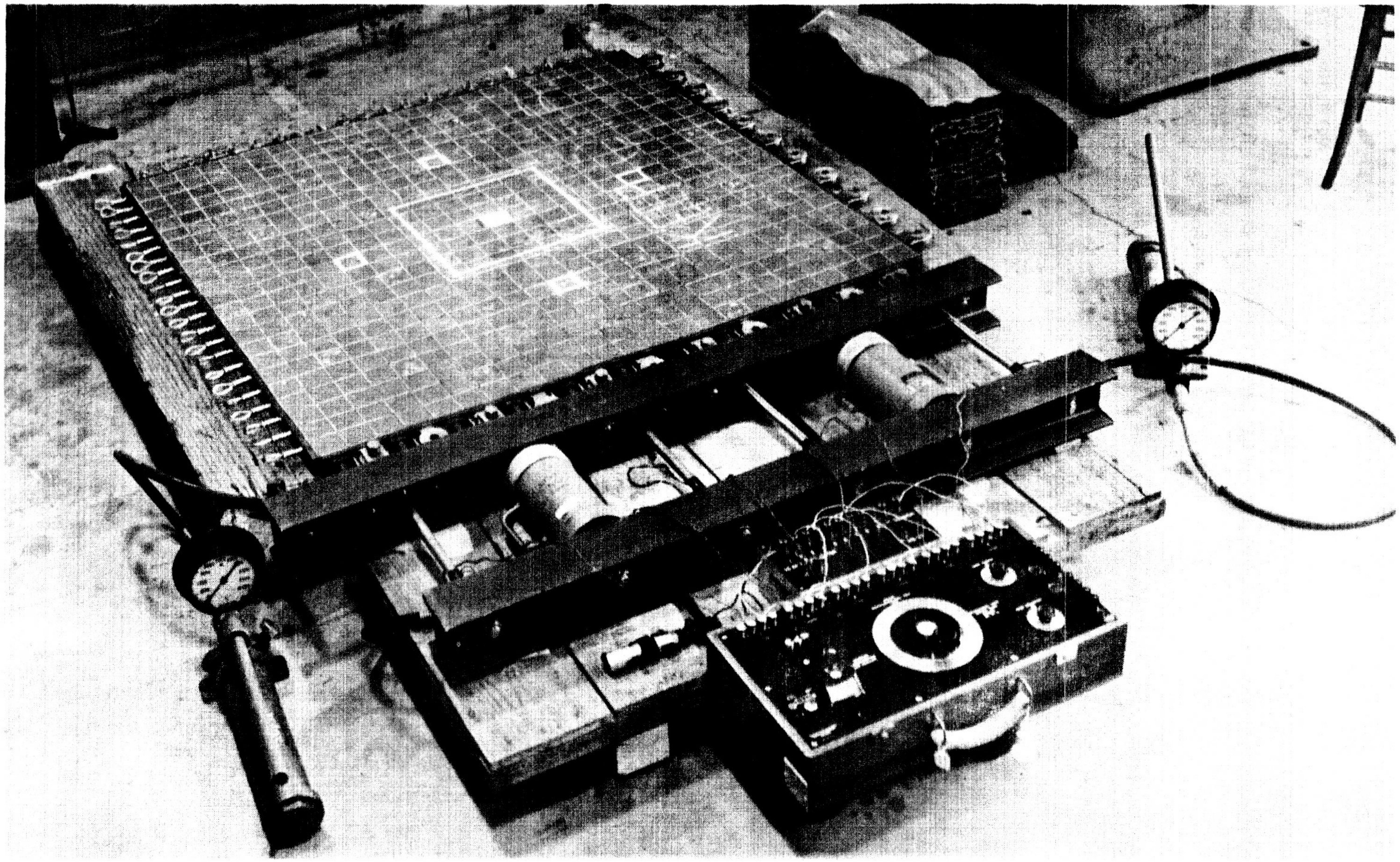
SLAB ASSEMBLY

FIGURE 2



SLAB ASSEMBLY DETAIL

FIGURE 3



PRESTRESSING OF SLAB

FIGURE 4

All plate bending tests were conducted at the same approximate level of prestress. The approximate tensile force on each cable was 750 pounds, and the approximate compressive stress on the ceramic was 720 psi.

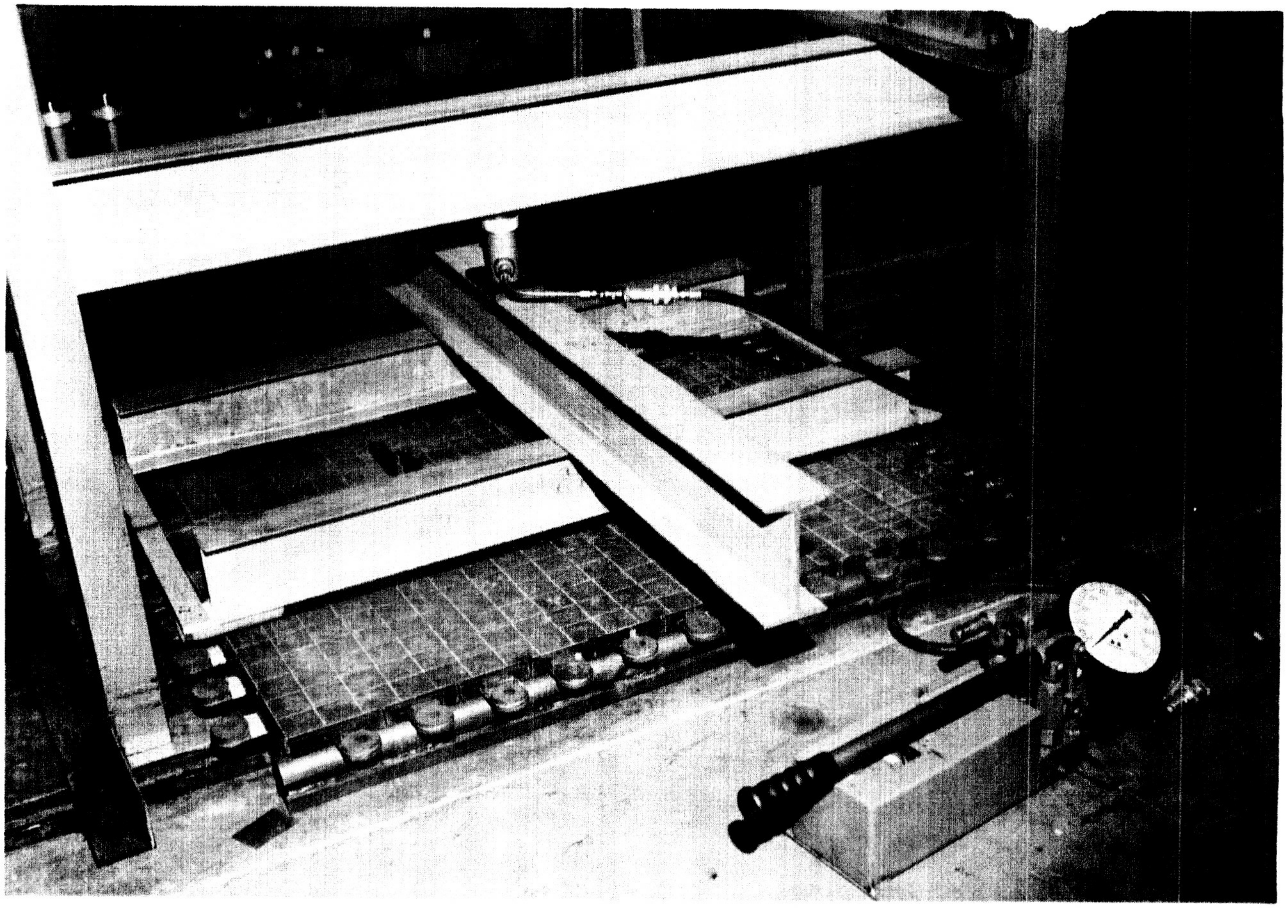
Subsequent bending tests showed that the bending was not uniform across the plate which implies that the plate prestress was not completely uniform. This probably resulted from the problem of locking-off the elongated cables at exactly the required strain (see Reference 7).

c. <u>Cylindrical Bending Tests</u>

Figure 5 is a photograph of a cylindrical bending test for the determination of D_x. The force to bend the plate was provided by a ten-ton jack and was transmitted to the plate through two aluminum I beams. Wooden half round cylinders, between the plate and the aluminum I beams, permitted rotation of the plate under a line load. Bending was restrained in the secondary direction by the I beams and by simple supports along the edges of the plate. These edge supports, round steel stock, were rigidly braced against the floor of the testing laboratory. The conditions of bending were such that the middle portion of the plate was subjected to a constant bending moment. Figures 6 and 7 indicate the location of the load lines and the location of the curvature measurements reported herein for cylindrical bending about the y and x axes, respectively. In each case three tests were made to measure the x and y curvatures.

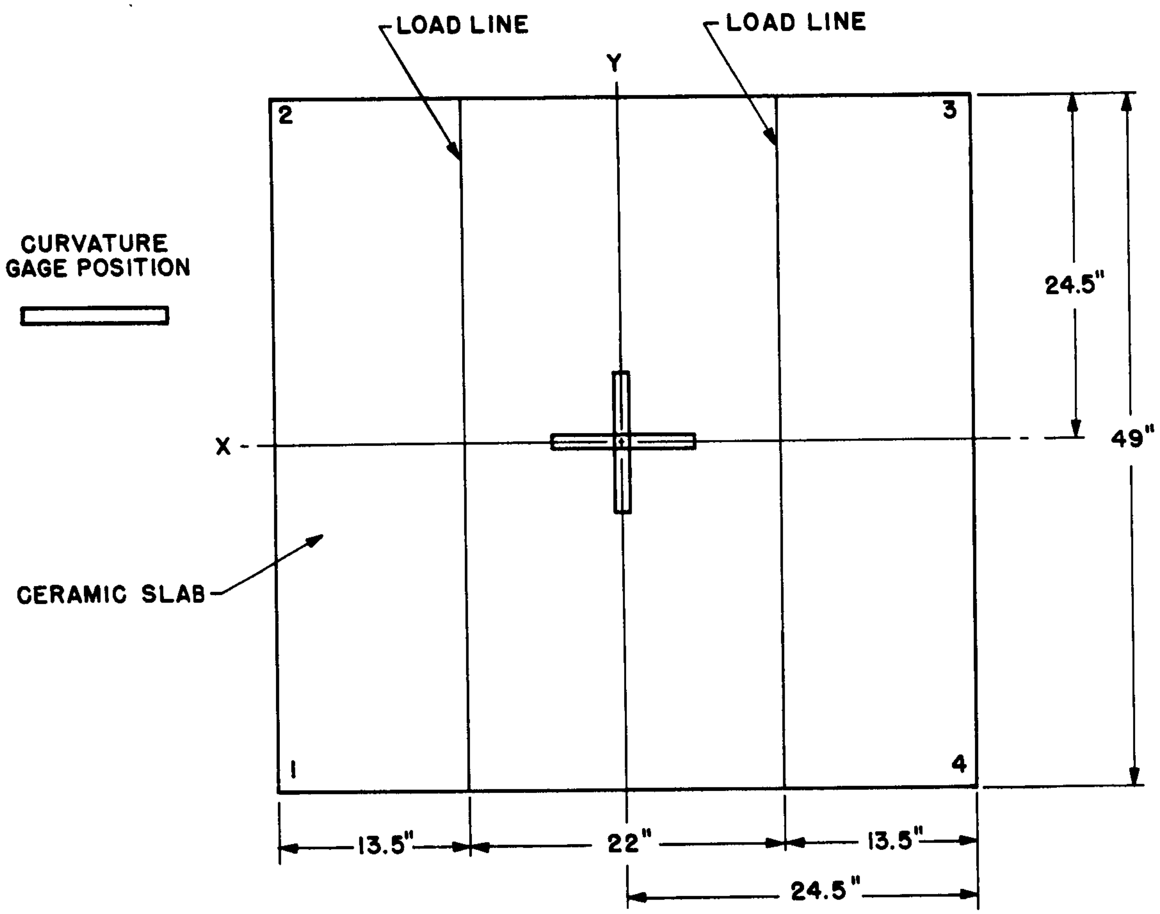
The plate curvatures were measured with a curvature gage which consisted of a dial gage mounted at the mid-point of a steel bar with two stationary legs (see Figure 8). When the plate was bent, the dial gage measured the relative deflection (i) between the middle and the end of the steel bar. The least reading of the gage was in one ten-thousandths of an inch. The average curvature between the ends of the gage may be shown to be given by the following equation:

$$1/R = \frac{2i}{j^2} \qquad (12)$$



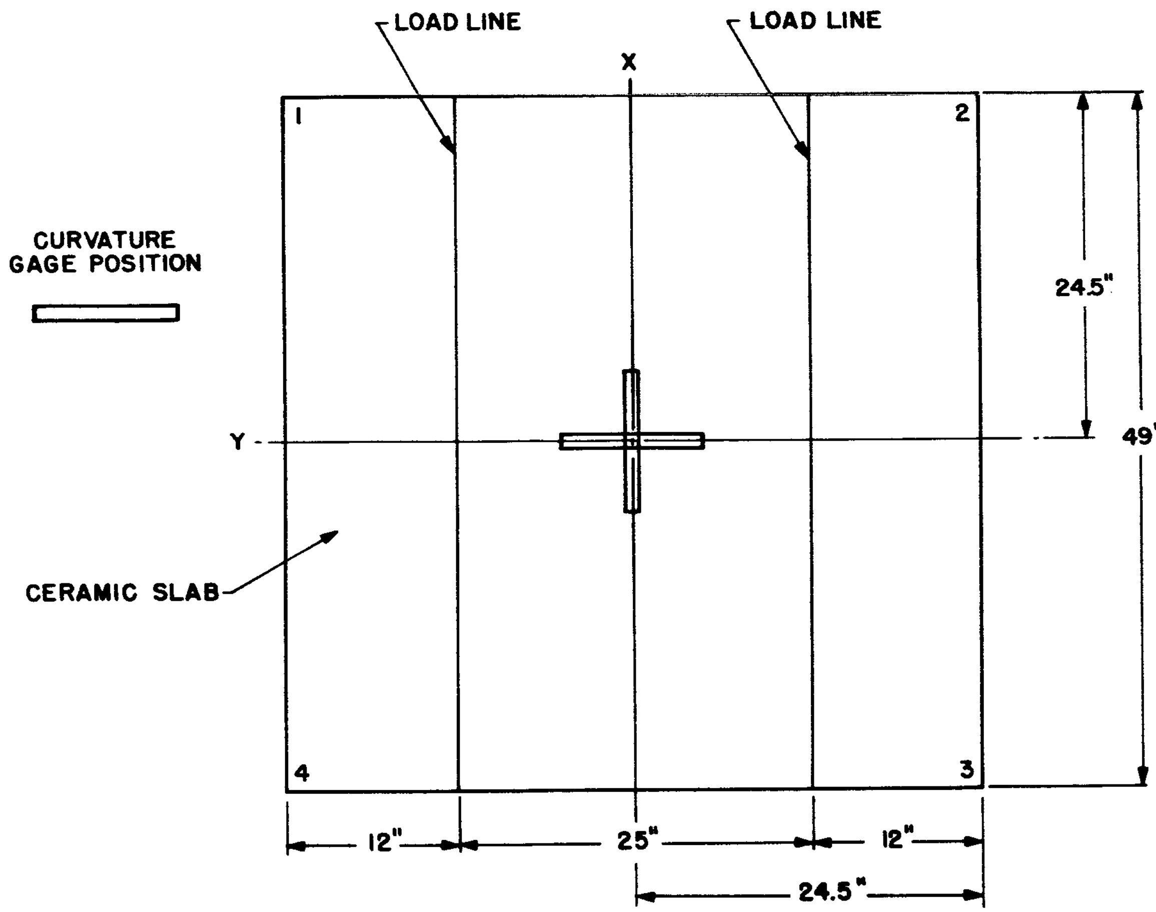
CYLINDRICAL BENDING TEST FOR DETERMINATION OF D_x

FIGURE 5



TEST SET-UP FOR D_x CYLINDRICAL BENDING ABOUT y-AXIS

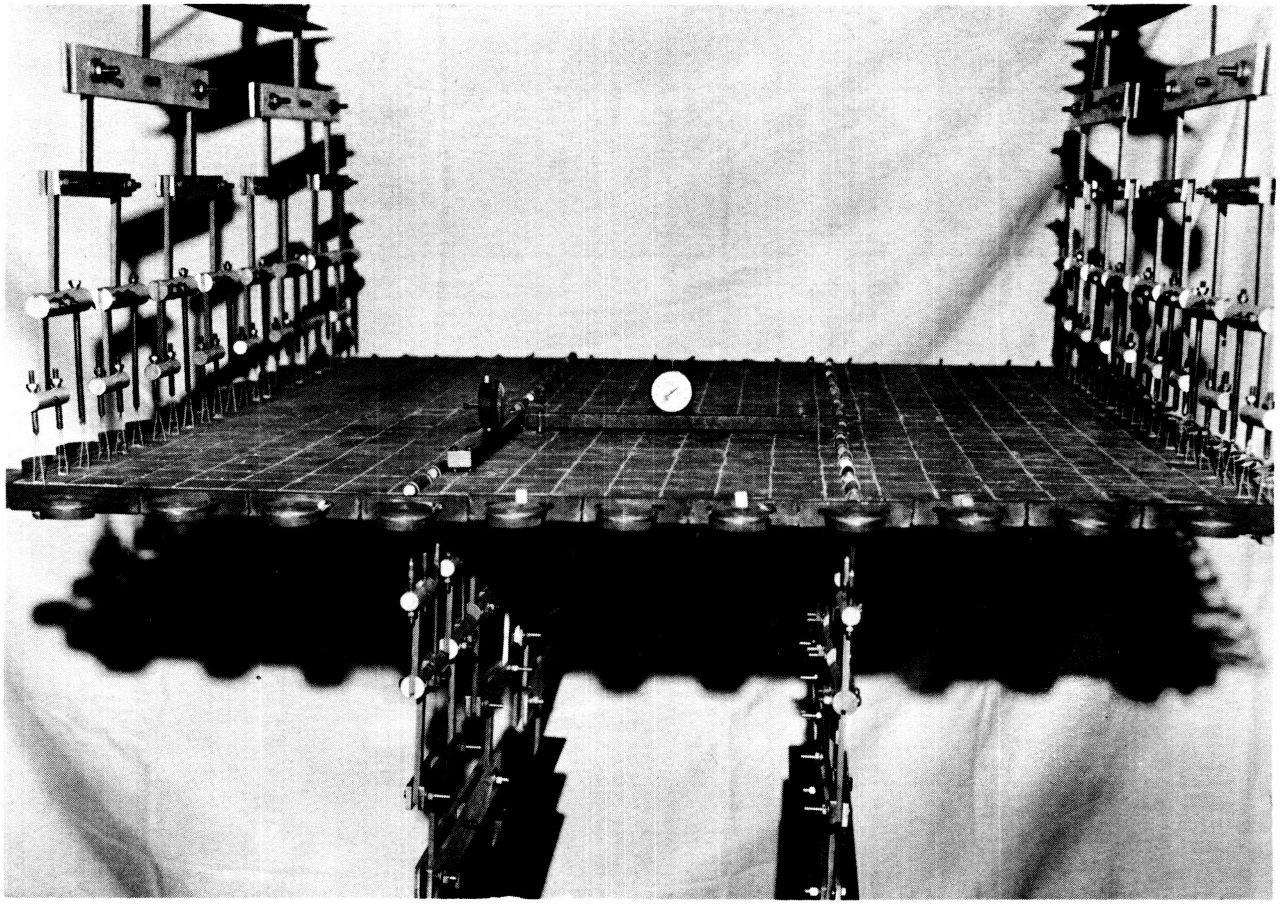
FIGURE 6



TEST SET-UP FOR D_y

CYLINDRICAL BENDING ABOUT x-AXIS

FIGURE 7



WHIPPLETREE FIXTURE WITH CURVATURE GAGES

FIGURE 8

where

R is the radius of the bent plate, inches

i is the deflection measurement, inches

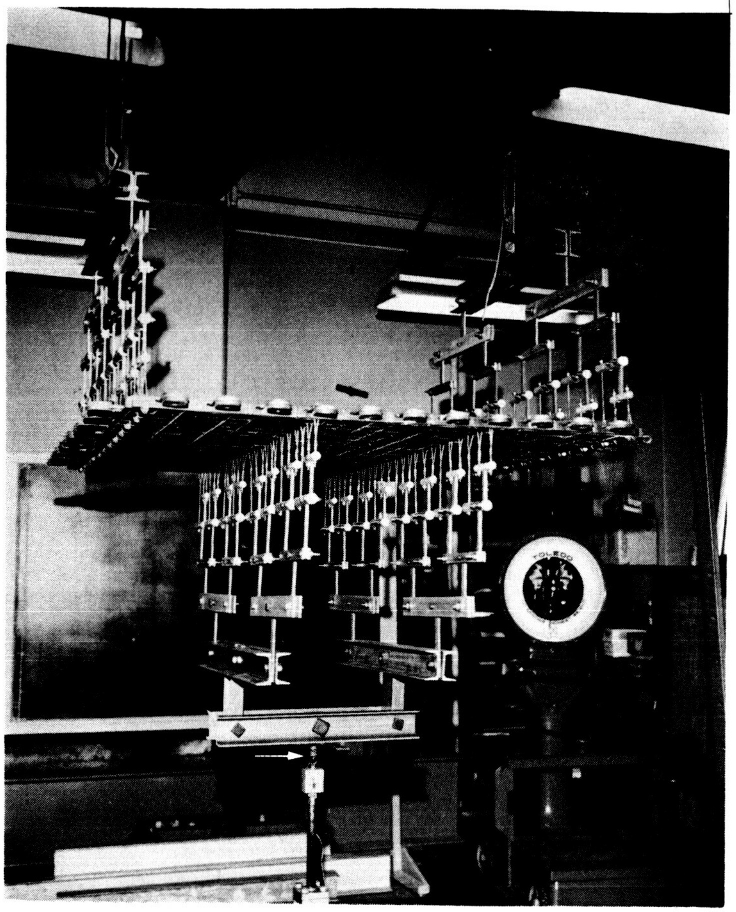
j is the distance between the gage probe and the stationary legs (j = 6.375"), inches

d. Anticlastic Bending Tests

An elaborate whippletree fixture was built to study anticlastic bending. Figures 8 and 9 are photographs of the whippletree fixture in use. The ceramic plate was attached to the whippletree fixture with high strength 0.042-inch diameter steel wires. The wires were passed between the ceramic blocks and were looped over half round aluminum bars. The ends of the wires were brazed to 1/4-inch diameter steel bolts, which attached to the whippletree fixture. Two fixtures were suspended from the ceiling of the testing room, and two fixtures were simultaneously loaded by a twenty-ton hydraulic jack which was attached to the floor of the testing laboratory, as shown in Figure 9. The force on the fixture was measured with a load-link that was located above the ram of the hydraulic jack, as indicated in Figure 9. Measurements of plate curvature were made at the locations indicated in Figure 10.

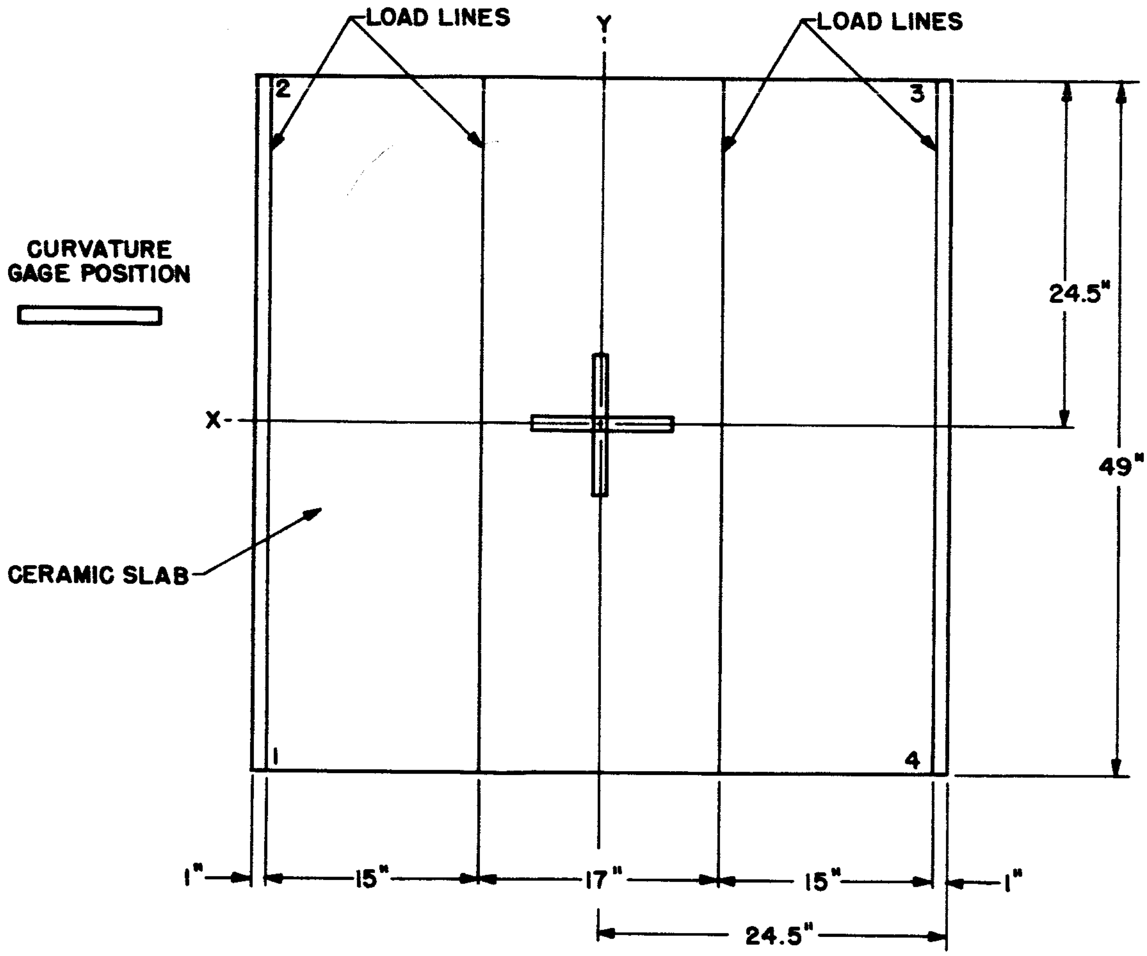
e. Twisting Tests

The plate was twisted by applying load to the corners of the plate as shown in Figure 11. The force to twist the plate was developed by a hydraulic jack that pushed up on one corner of the plate. The pressures in the jack, during loading, were recorded and were later converted to forces with a jack calibration curve. The adjacent corners of the ceramic plate were held down by two twenty-ton jacks. The fourth corner was held up with an aluminum half-round bar which rested on the floor of the testing laboratory. The deflections of the plate, at the corner over the hydraulic jack, were measured with a dial gage. The corners of the plate were numbered as shown in Figure 10. Test I was conducted with diagonal 1-3 concave upward and Test II was for diagonal 2-4 concave upward.



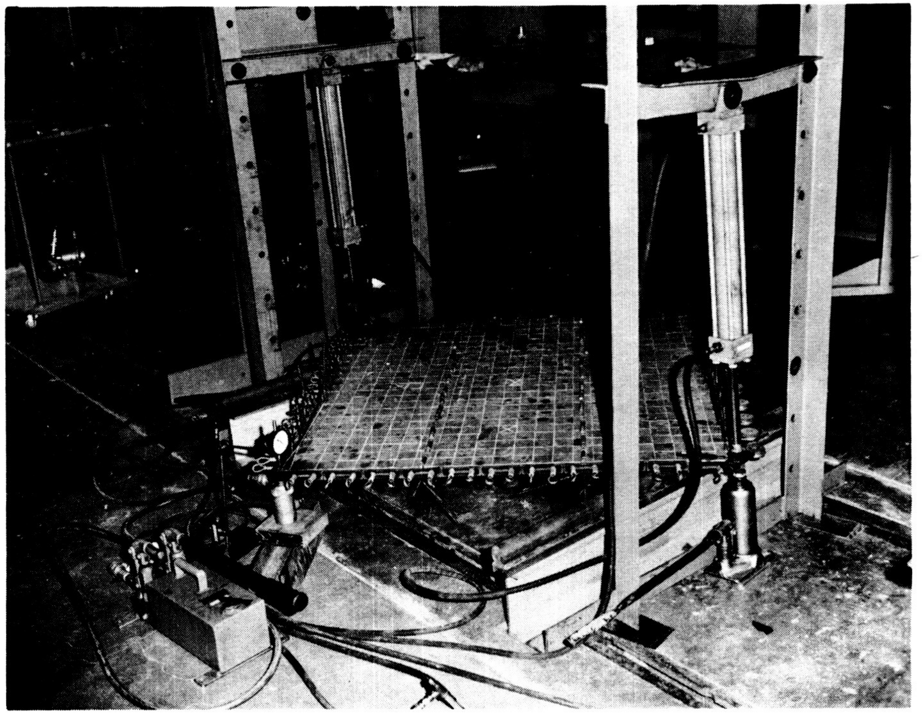
WHIPPLETREE FIXTURE WITH LOAD LINK

FIGURE 9



ANTICLASTIC BENDING TEST,
BENDING ABOUT THE y-AXIS

FIGURE 10



TWISTING TEST FOR DETERMINATION OF D_{xy},
FRONT SIDE

FIGURE 11

III. EXPERIMENTAL RESULTS

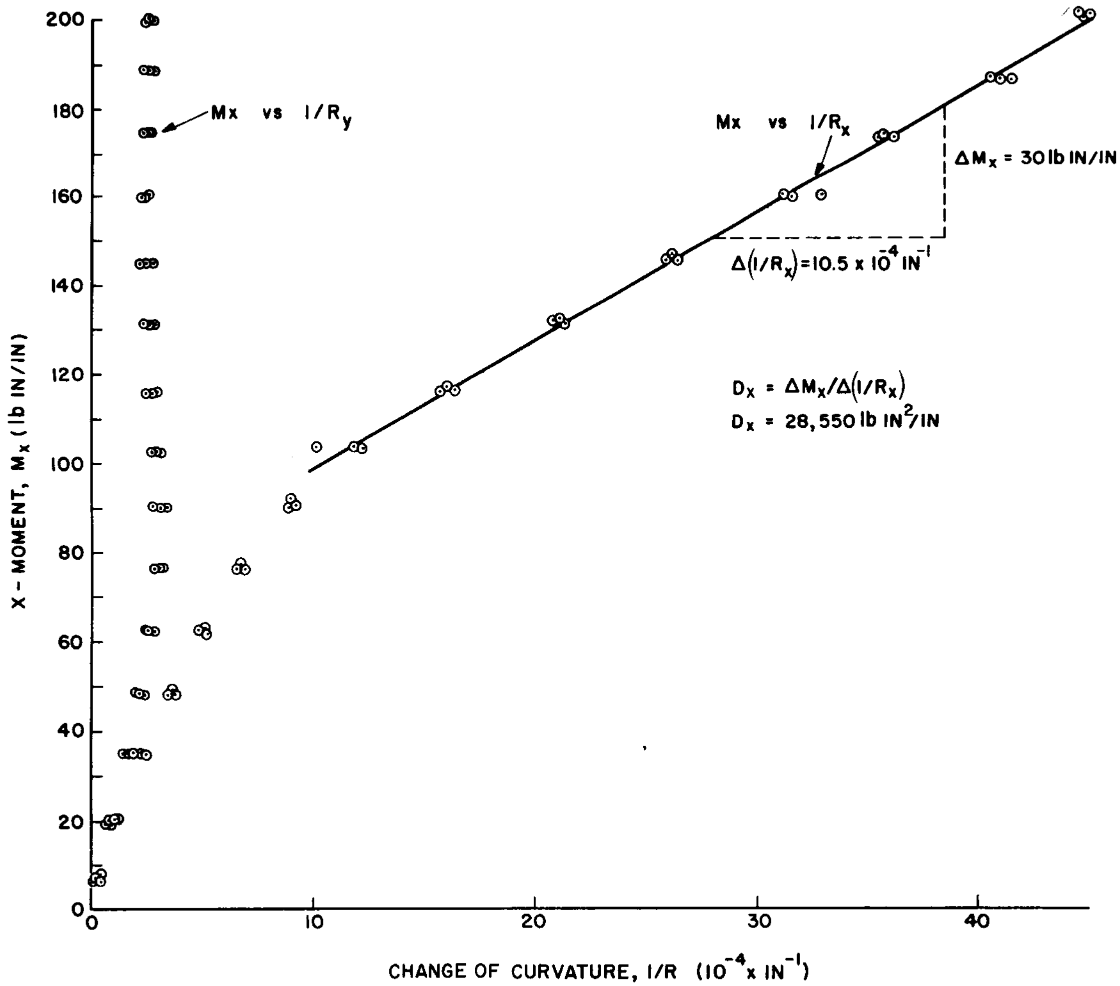
a. Cylindrical Bending

The bending moments are plotted against the plate curvatures in Figure 12 for bending about the y axis and in Figure 13 for bending about the x axis. The graph of the moment versus primary curvature ($1/R_x$) in Figure 12 is linear at high values of bending moment and is nonlinear at low values of bending moment. This is a result of two actions: 1) secondary bending due to initial warpage of the plate, and 2) separation of the blocks due to the low level of prestress. At low values of bending moment secondary bending took place as the fixture acted to straighten out the initial distortion of the plate in the secondary direction. Cylindrical bending took place after the secondary bending reached an equilibrium value as indicated in the M_x versus $1/R_y$ plot in Figure 12. As the M_x versus $1/R_y$ curve approached the equilibrium value, the slope of the M_x versus $1/R_x$ plot (on the same figure) became constant. The slope of the M_x versus $1/R_x$ plot is equal to the flexural stiffness D_x as is given in Equation (7). The stiffness D_x from Figure 12 and the stiffness D_y from Figure 13 were found to be 28,550 lb-in.^{2}/in. and 13,450 lb-in.^{2}/in., respectively. The flexural stiffness D_x was greater than D_y because the cables in the x direction were lower by 3/32 inch than those in the y direction.

b. Anticlastic Bending

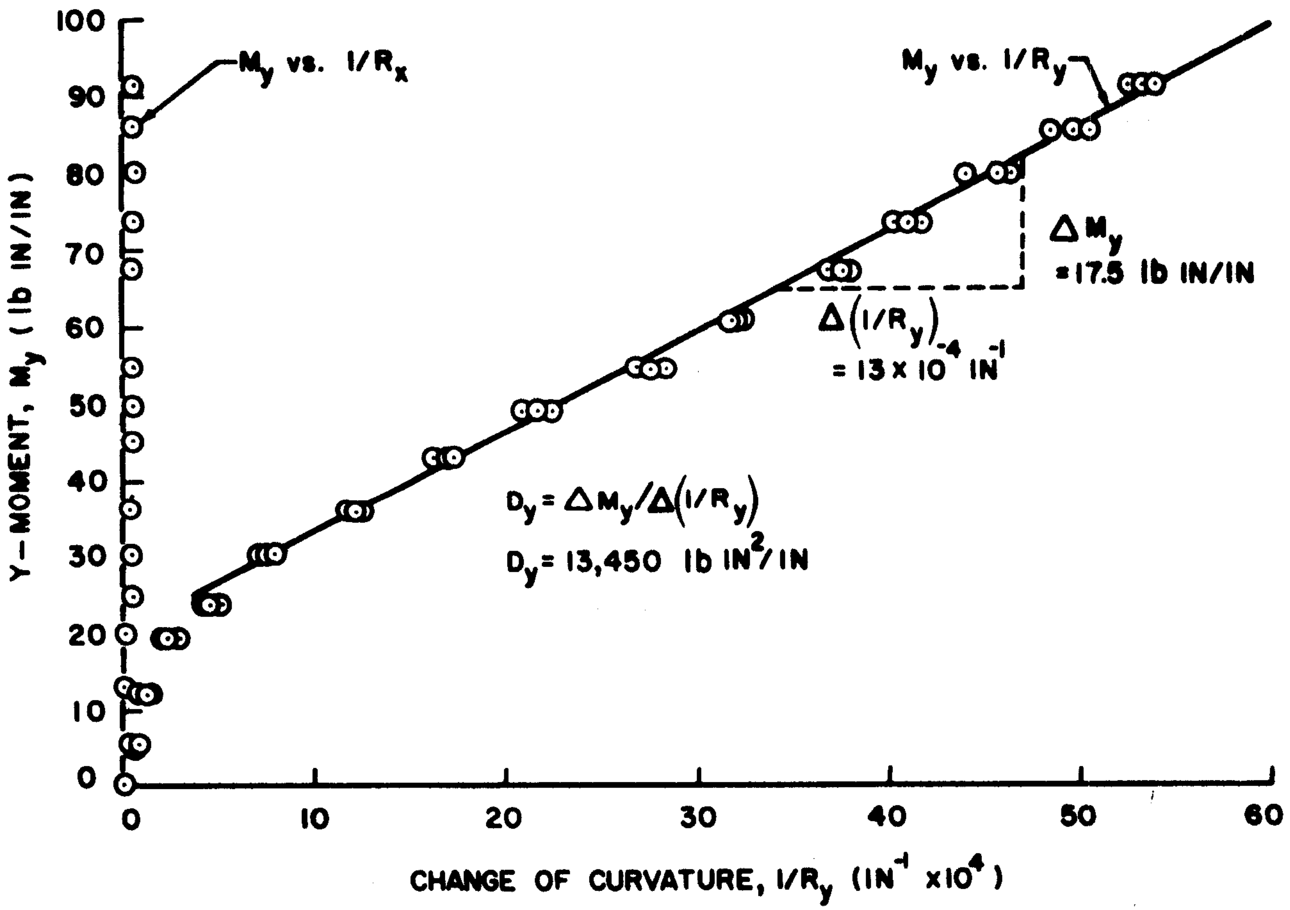
The whippletree fixture permitted the plate to bend in an anticlastic manner. R_x is plotted against R_y on Figure 14; and D_1, calculated with Equation (10), was found to be 305 lb-in.^{2}/in.

The Poisson stiffness D_1 was also calculated with Equation (10) but the value obtained for D_1 seemed unreasonably high. The flexural stiffness from the anticlastic bending test in Figure 15 and the D_x from the cylindrical bending test in Figure 12 were used together in the calculation. In Equation (10) the accuracy of the secondary curvature $1/R_y$ is very important. The curvature $1/R_y$ was close to zero and it was divided



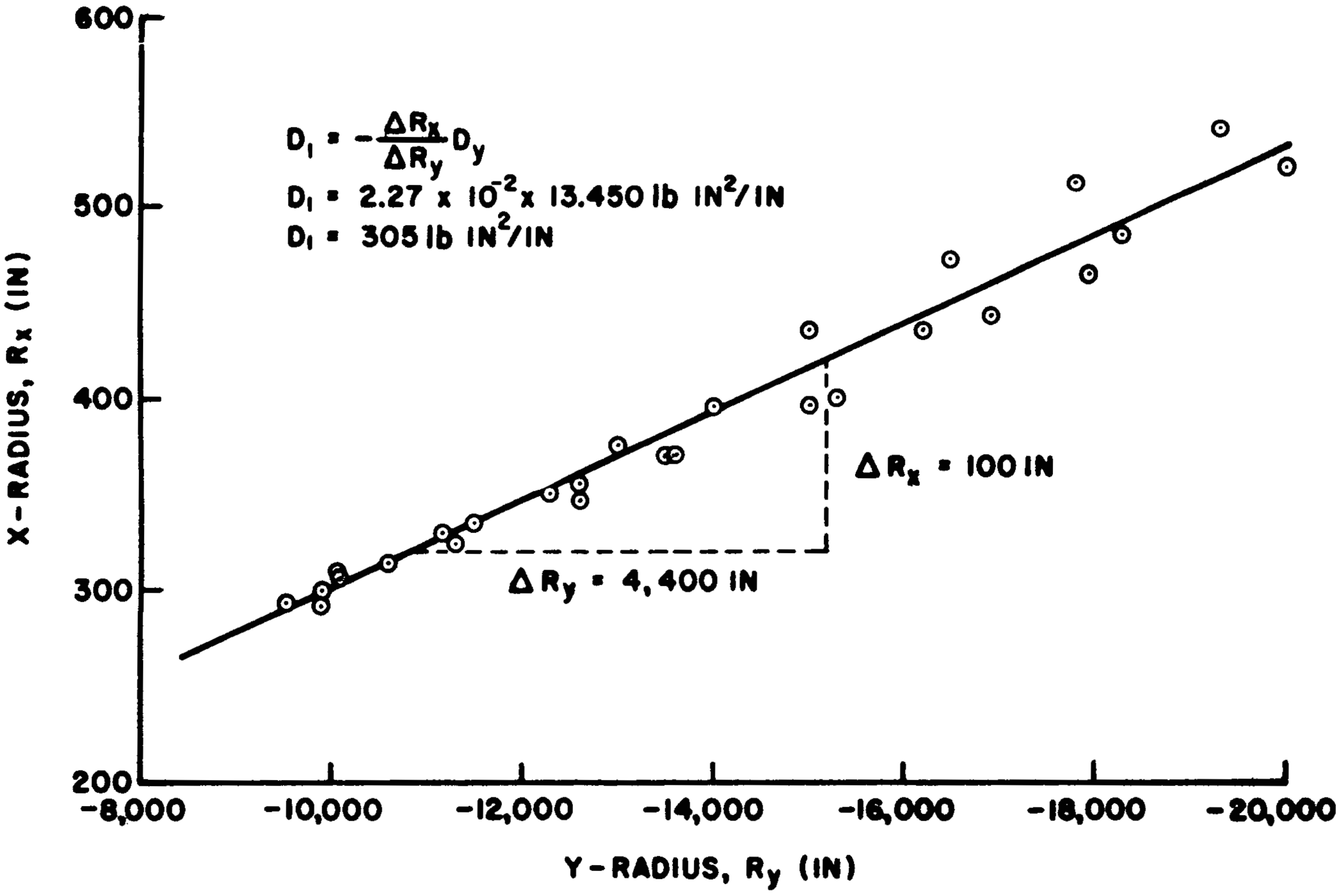
MOMENT VERSUS CURVATURE FOR CYLINDRICAL BENDING ABOUT THE y-AXIS

FIGURE 12



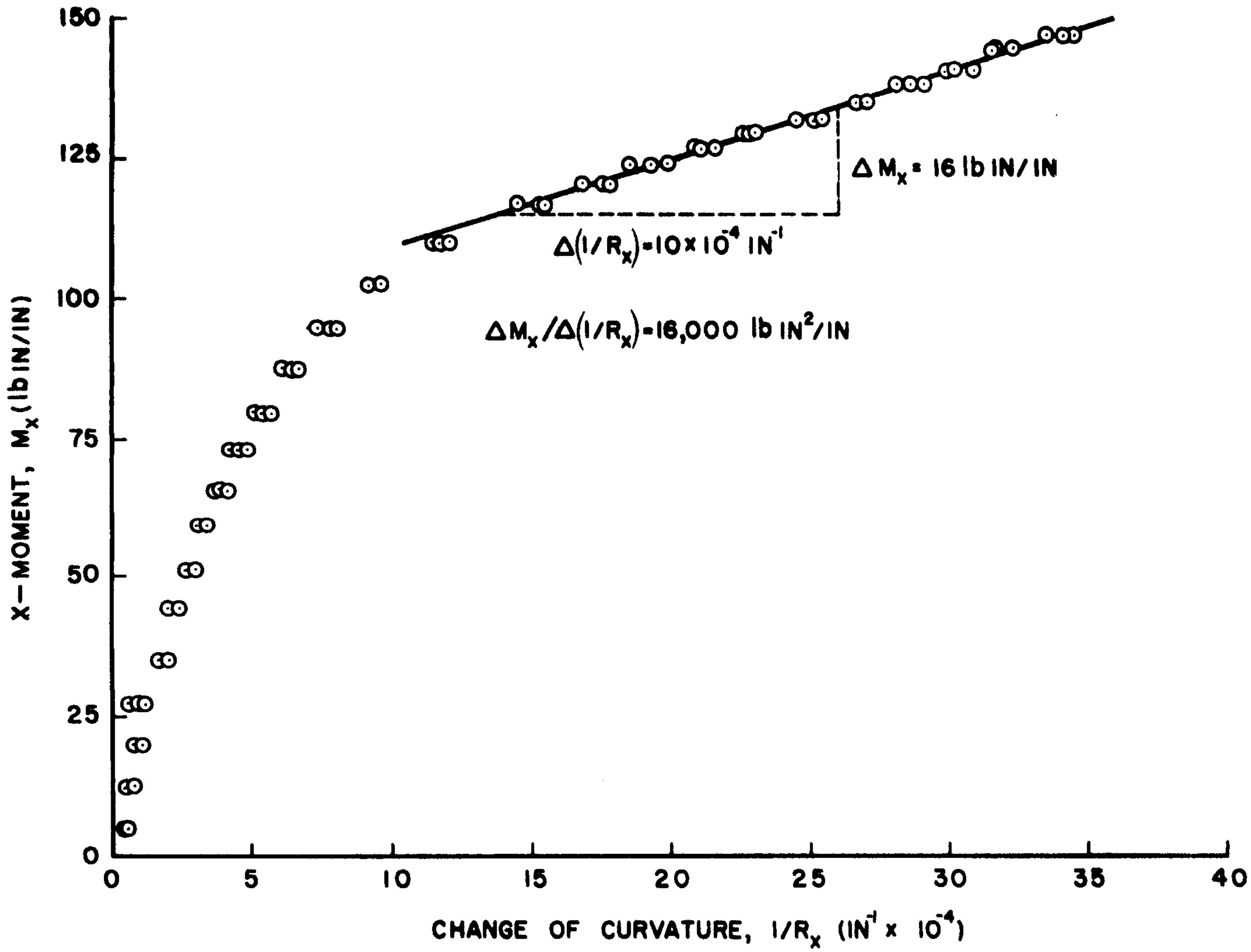
MOMENT VERSUS CURVATURE FOR CYLINDRICAL BENDING ABOUT THE x-AXIS

FIGURE 13



RADIUS-y VERSUS RADIUS-x ANTICLASTIC BENDING TEST

FIGURE 14



MOMENT VERSUS CURVATURE; ANTICLASTIC BENDING TEST, BENDING ABOUT y-AXIS

FIGURE 15

into a number of significant size. Only a small change in $1/R_y$ caused a large change in the value of D_1.

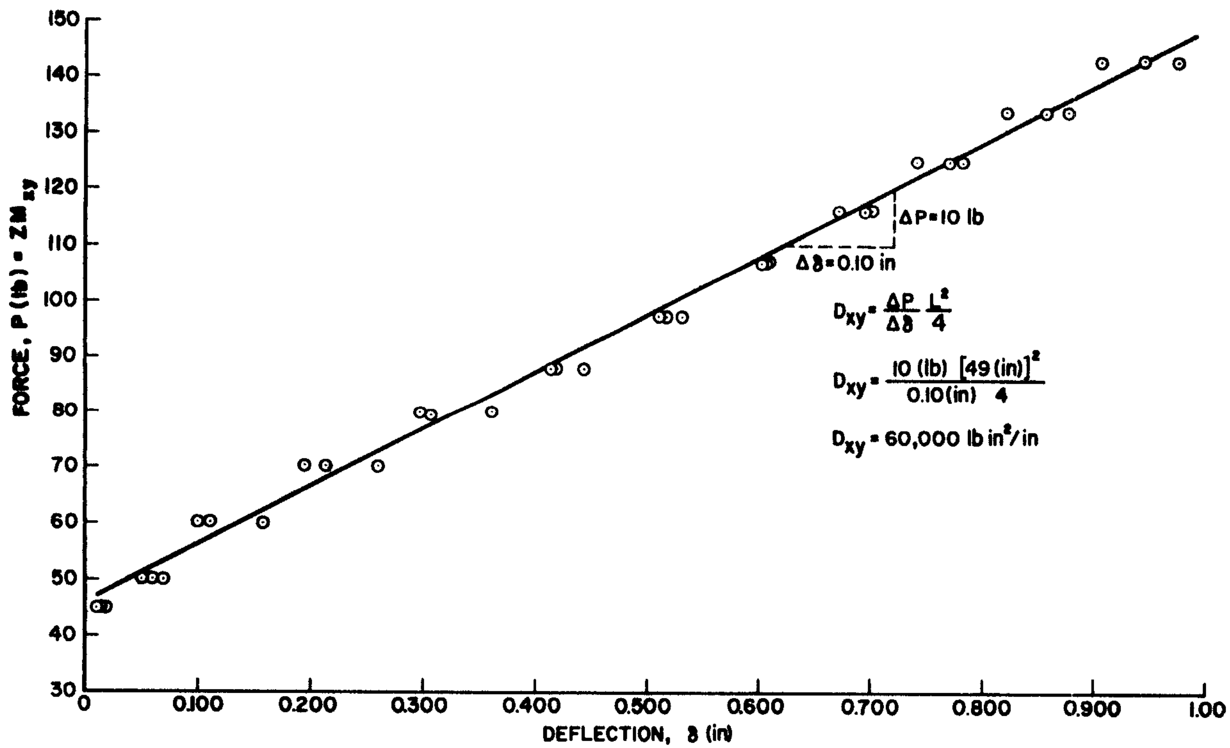
In anticlastic bending the Poisson effect, the ratio of secondary strain to primary strain, was small because there was very little secondary strain at the low level of plate prestress. This was so because the ceramic blocks separated on the tension side of the neutral axis and did not elongate. On the compressive side of the neutral axis the asbestos gasketing material was compressed more than the ceramic. In either case the secondary strains were too small to cause a significant Poisson effect at this level of prestress.

c. Twisting

The reduced data for twisting test I is given in Figure 16. Similar results were obtained from twisting test II. The force P was plotted against the corner deflection δ. The twist stiffness D_{xy} is the slope of the P over δ multiplied by a constant, as can be seen from Equation (11). The P versus δ plots were relatively linear, so the twisting stiffness D_{xy} was also constant. D_{xy} was 60,000 lb-in.^{2}/in. and 64,000 lb-in.^{2}/in. for Tests I and II, respectively. An average value of 62,000 lb-in.^{2}/in. was taken for the average experimental twisting stiffness.

This value of twisting stiffness is inaccurate because it depends to a large degree on the nature of the corner supports. The two corners in question were reacted by twenty-ton hydraulic jacks as shown in Figure 11. Tests I and II were made in the same way by having the jacks press against the corner ceramic blocks and steel edge plates. A larger twist stiffness can be obtained by having the jacks press farther in from the corners. Local block deformation at the corners of the plate also made the data erratic.

The twisting stiffness D_{xy} was considerably larger than the flexural stiffness D_x or D_y. In plate twisting the blocks did not separate, so the entire cross section was effective in resisting the twisting moments.



FORCE VERSUS DEFLECTION FOR TWISTING TEST I

FIGURE 16

In cylindrical bending only the top sections of the blocks were stressed and not the whole cross section because the bottom portions of the blocks were separated due to the bending. Therefore, the twisting stiffness was higher than the flexural stiffness because of a larger effective contact area of the ceramic under twisting.

d. Cracking of the Ceramic Blocks

A number of the ceramic blocks in the segmented plate were cracked. Most of the cracks ran at forty-five degrees from the edge grooves to the top surface of the blocks, on the compressive side of the neutral axis. Other blocks were split into two pieces along their center line in the xy plane. Even though the working loads were kept within their allowable limits, cracking occurred probably because of compressive stress concentrations. Although a number of the ceramic blocks were cracked, the segmented plate retained most of its load-bearing capacity. To minimize cracking, great care should be taken in the construction of the ceramic blocks, in the fitting of the gasketing, in the selection of the ceramic material, and in assembly of the slabs.

IV. PLATE STIFFNESS CONSTANTS DETERMINED FROM THE GEOMETRIES OF THE CROSS SECTIONS

An expression for the flexural stiffness D for a cross section of a reinforced concrete slab is given in Reference 14 as follows:

$$D = \frac{E_c}{1-\mu_c^2}\left[I_c + n\,I_s\right]$$

where

E_c = modulus of the slab material

μ_c = Poisson ratio of slab = 0.25

I_c = moment of inertia of the slab

I_s = moment of inertia of the steel

$n = \frac{E_s}{E_c}$ is the ratio of the moduli

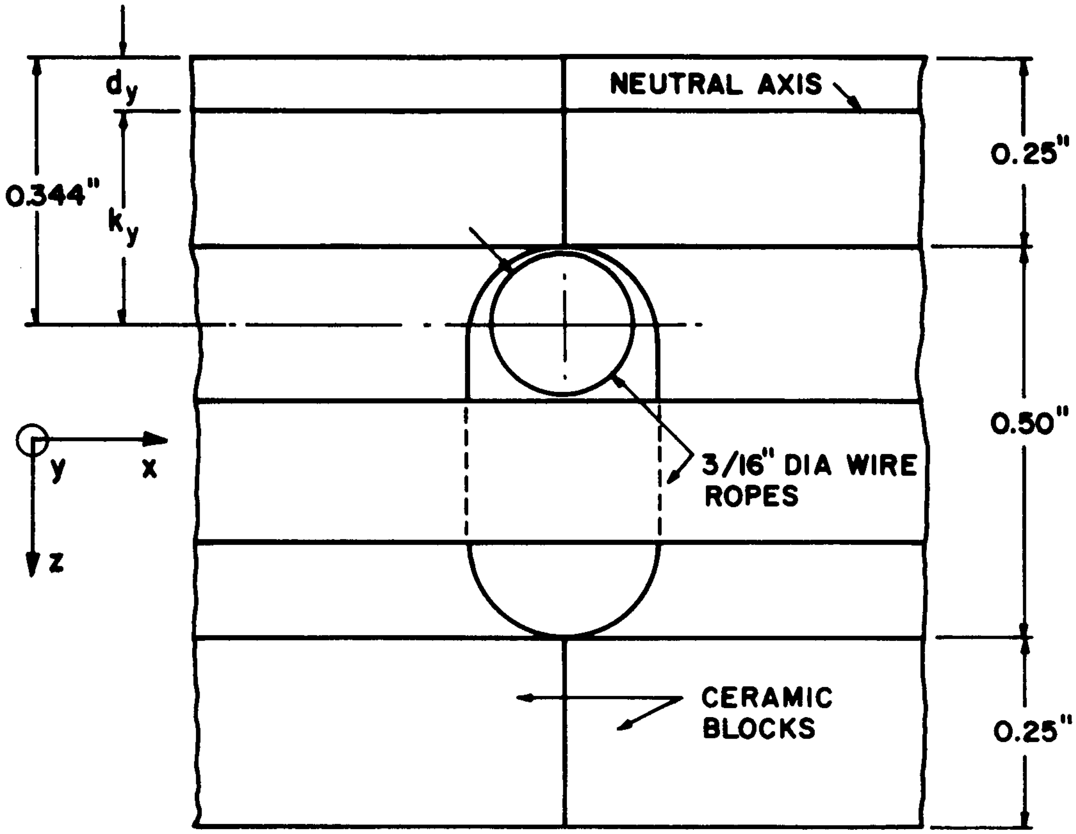
This can be applied to the prestressed ceramic slab at the level of prestress used by considering it to be a cracked section of the concrete slab.

The plate cross section in the x direction is shown in Figure 17 and that in the y direction in Figure 18. The steel wire ropes were spaced between the ceramic blocks and are two inches apart. Each wire rope contained seven strands of cable with each strand containing nineteen individual wires which were 0.012 inches in diameter. In using the above equation, the modulus of elasticity of the wire rope was assumed to be a typical value as given in a handbook on wire rope (see Reference 16).

From the above equation the flexural stiffnesses D_x and D_y were found to be:

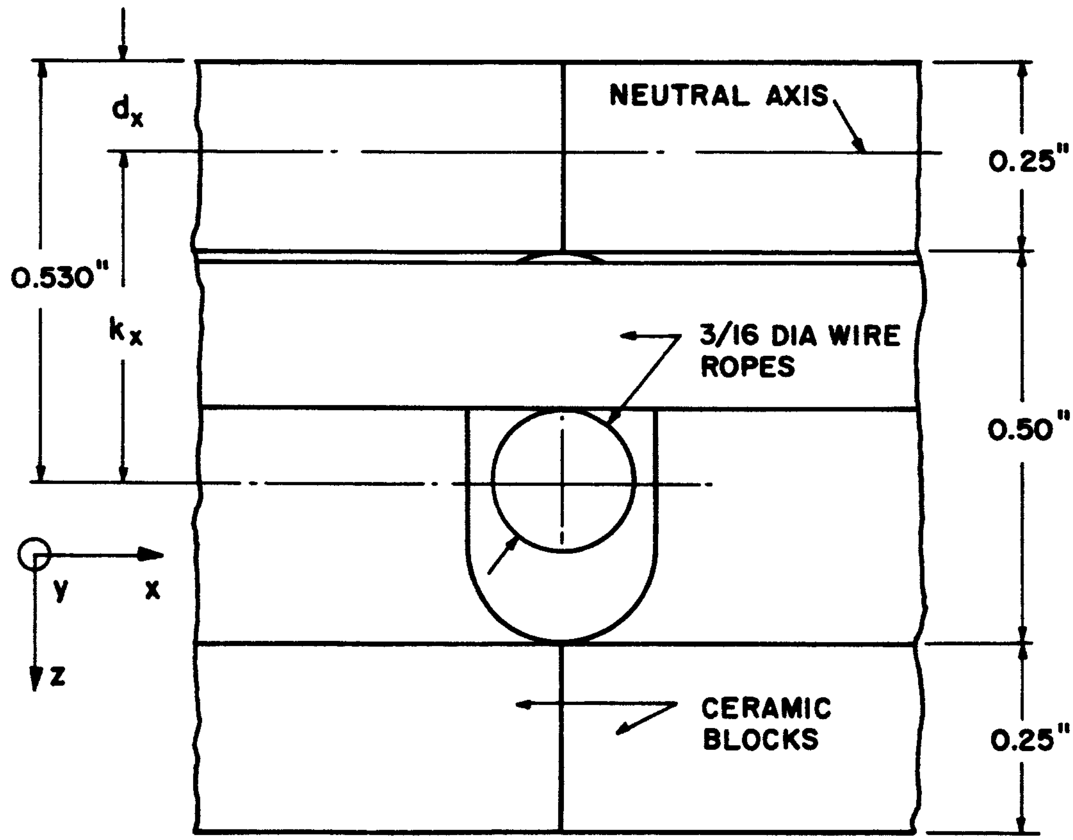
D_x = 37,300 lb-in.^{2}/in.

D_y = 13,300 lb-in.^{2}/in.



y CROSS SECTION OF PLATE

FIGURE 17



x CROSS SECTION OF PLATE

FIGURE 18

An expression for the Poisson plate stiffness D_1 is given in Reference 14,

$$D_1 = \mu_a \sqrt{D_x D_y}$$

so that

$$D_1 = 5,560 \text{ lb-in.}^2/\text{in.}$$

The plate twist stiffness D_{xy} was obtained by an integration over the top and bottom portions of the ceramic blocks.

$$D_{xy} = \frac{E_c}{2(1+\mu_c)} \left[\int_{-\frac{1}{2}}^{\frac{1}{4}} z^2 \, dz + \int_{\frac{1}{4}}^{\frac{1}{2}} z^2 \, dz \right]$$

and found to be:

$$D_{xy} = 156,000 \text{ lb-in.}^2/\text{in.}$$

V. SUMMARY AND CONCLUSION

The experimental flexural stiffnesses of this prestressed ceramic plate were constant at high values of bending moment, and their magnitudes depended most significantly on the locations of the prestressing cables in the ceramic blocks. The plate was orthotropic, with Dx about twice as large as Dy. In plate bending the top portions of the ceramic were in compression, and the bottom portions of the blocks on the tensile side of the neutral axis were separated and were stress free. The blocks did not separate in the twisting test. As a result, the twist stiffness Dxy was considerably higher than the flexural stiffnesses Dx or Dy. The Poisson stiffness or secondary strain effect was small at the low level of prestress because the blocks separated on the tension side of the neutral axis; whereas on the compressive side of the neutral axis the gasketing material was compressed more than the ceramic. Considerable cracking of the ceramic material occurred in the segmented plate because of compressive strain concentrations, but the plate retained most of its load-bearing capacity. The following table lists the experimental and analytical plate stiffnesses for center of the plate.

PLATE CONSTANT	EXPERIMENTAL	ANALYTICAL
Dx	28,550 lb-in.^{2}/in.	37,300 lb-in.^{2}/in.
Dy	13,450 lb-in.^{2}/in.	13,300 lb-in.^{2}/in.
D_{xy}	62,000 lb-in.^{2}/in.	156,000 lb-in.^{2}/in.
D_1	305 lb-in.^{2}/in.	5,560 lb-in.^{2}/in.

The experimental and analytical values for D_y may be seen to be in close agreement. In the calculation for D_x, the distance from the top of the block to the x direction wire rope (equal to 0.530 inch) was probably assumed to be too great because the wire ropes during plate bending were displaced towards the top of the cross section, which would make the analytical value of D_x too large. The analytical stiffnesses D_{xy} and

D_1 were also considerably larger than the experimental values. This was so because the elastic modulus E_c that was used in the analytical calculation undoubtedly was larger than the effective E of the composite plate. The effective elastic modulus of the composite plate is an unknown function of the elastic and plastic properties of the gasket separated ceramic. In view of the above considerations, the agreement between the experimental and analytical plate stiffness constants is considered to be good.

This investigation showed how a segmented plate can be treated as a continuous orthotropic plate. The segmented plate is discontinuous, but it is believed that its overall bending behavior is predictable utilizing the small deflection theory of elastic plates and average properties such as those determined herein. This investigation should be considered to be a preliminary study pointing the way to a more refined study of prestressed ceramic slabs.

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