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Investigation of steel reinforced wood laminated beams

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AN INVESTIGATION OF STEEL REINFORCED WOOD LAMINATED BEAMS

by

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Acknowledgement is made to the Anaconda Forest Products Company for the donation of materials and facilities for laminating and to the Shell Chemical Company for their donation of the epoxy resin formulation used in this study.

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CHAPTER I

INTRODUCTION

Wood beams have long been recognized as a favorable structural material, but due to certain characteristics there are limitations to their use. Although wood is among our strongest structural materials on a pound-for-pound basis, it has a disadvantage in that a pound of wood generally has greater bulk volume per pound than its structural competitors. This, plus the fact that there may be some variability in strength and stiffness between wood beams of the same size limits the use of wood beams in some construction situations.

The objective of this study is to determine if there is a significant increase in strength (modulus of rupture) and stiffness (modulus of elasticity) which may be gained by reinforcement of wood laminated beams with steel strapping. If there is a significant increase in strength and stiffness by reinforcement, this study is to ascertain in what portions of the wood beam this reinforcement is most significantly effective.

If, by reinforcing wood beams, it is possible to increase their strength and stiffness significantly, it will be possible to use beams of less bulk, compared to the conventional laminated wood beam, to provide sufficient support for a given load while remaining within the accepted limits of deflection. This should enhance the future potential for wood beams in construction in situations where wood may be subject to criticism.

As pertains to this study, reinforcing is the bonding of steel strapping between the wood laminae in different portions of the wood laminated beam. This reinforcing material was bonded to the wood with an epoxy resin formulation.

An epoxy resin formulation was chosen for bonding the metal to the wood since with epoxy "the effectiveness of the bond formed with wood, metal, ... is classified as excellent".[1] It has also been mentioned that epoxy resin adhesives have favorable bending properties.[2] It was of utmost importance to use the best possible bonding agent available to determine if the reinforcing material would have any effect on the properties of the beams without any doubt interjected by possible bonding weaknesses.

Several methods have been investigated by past researchers in seeking to improve the strength and stiffness of wood beams. One such method involved fabricating laminated beams from two species of wood.[3] Other studies have dwelt with the use of aluminum bonded to wood.[4]

The report pertaining to the use of two species of wood was basically concerned with increasing the strength and stiffness of a weaker species of wood by bonding to it a species of wood having a greater density. By this means it would be possible to use lower density wood in the center portion of the laminated beams while still retaining favorable strength and stiffness. This study does not infer that by this means it is possible to use less bulk to support a given load but deals with better utilization of low density material.

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[1] E. Preiswerk and J. Charlton, "Ethoxylines: What They Are; Where They Are Going," Modern Plastics, XXVIII (3) (November, 1950), 102.

[2] Jerome Formo and Luther Bolstad, "Where and How to Use Epoxies," Modern Plastics, XXXII (11) (July, 1955), 99.

[3] Robert L. Ethington, "Stiffness and Bending Strength of Beams Laminated From Two Species of Wood," U.S. Forest Products Lab. Rept. No. 2156 (1953), 28 pp.

[4] Alan Sliker, "Reinforced Wood Laminated Beams," Forest Products Journal, XII (2) (February, 1962), 91: Richard Mark, "Wood-Aluminum Beams Within and Beyond the Elastic Range," Forest Products Journal, XI (10) (October, 1961), 477.

The studies dealing with wood-metal combinations were based on the reinforcement of wood beams with aluminum sheets. Both investigators observed that, by reinforcing, there was an increase in strength and stiffness of the experimental beams. Sliker[1] also noted that the most practical location of the reinforcing material within the wood beam would be in the top and bottom portions.

Aluminum is not recognized as a suitable structural material since under short term loading it will stretch and under constant loads it is subject to creep properties. It is this author's feeling that studies pertaining to structural applications should use a material having favorable structural properties; for this reason high tensile strength steel strapping was used in this study. Another reason for pursuing this topic is that past studies have been based on relatively small samples and there was no mention in the publications of a statistical analysis of the results. Therefore, in this study the sample used was larger than those used in previous studies and the data was analyzed at the 95 per cent level of confidence.

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1. Alan Sliker, "Reinforced Wood Laminated Beams", Forest Products Journal, XII (2) (February, 1962), 91.

CHAPTER II

METHODS AND PROCEDURE

I. BEAM TYPE AND FABRICATION

Ninety experimental beams were made. Forty were categorized as reinforced; forty were used as an epoxy control (the epoxy resin formulation was used in the same glue lines as it previously was used to adhere the metal to the wood); and ten beams were used as a resorcinol-phenol control (Resorcinol-phenol was used exclusively as the adhesive in their fabrication). All beams were comprised of six wood laminae and tested with the laminae in the horizontal position. The beams were 48 inches in length, 1.25 inch in width and of a variable depth, ranging from 3.00 to 3.17 inches. The control and epoxy control beams had a depth of 3.00 inches; the reinforced beams, type A and B, had a depth of 3.04 inches; the reinforced beams, type C, had a depth of 3.07 inches; and the reinforced beams, type D, had a depth of 3.17 inches. These depth variations were due to the added thicknesses of steel and to the fact that manufacturers recommendations called for a heavier spread and lower clamping pressures for the epoxy resin used than that recommended for the resorcinol-phenol.

Four types of reinforced beams were fabricated. In type A, metal was glued into the top glue line only; in type B, metal was glued into the bottom glue line only; in type C, metal was glued into the top and bottom glue lines; and in type D, metal was glued into all glue lines. (See Figure 1).

The species of wood used as Inland Region Douglas fir (Pseudotsuga menziesii). Laimae 48 inches by 1.25 inches by 0.5 inches were used to make the beams. The wood selected was free of visible defect, flatsawn, kiln dried, surfaced on four sides with from eight to twelve rings per inch.

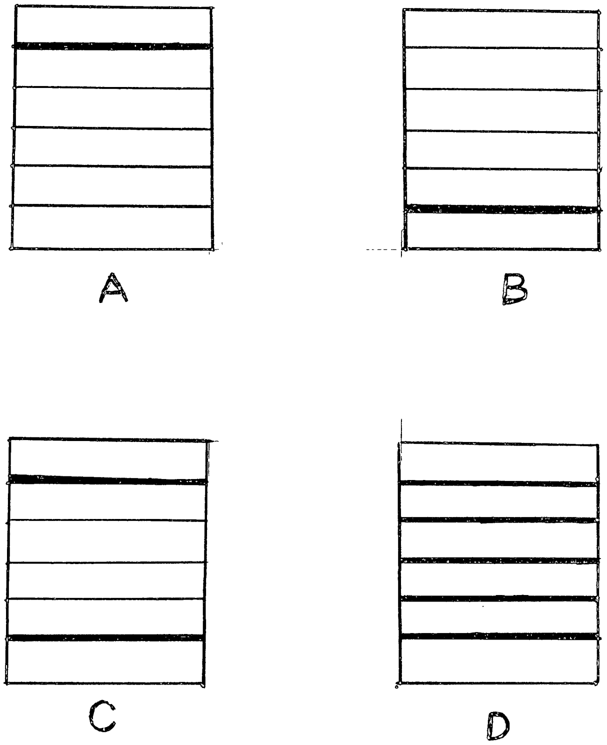


FIGURE I. CROSS SECTIONS OF THE REINFORCED LAMINATED TEST BEAM TYPES.

The reinforcing material was a heavy duty steel strapping, 1.25 inches wide and 0.034 inches thick. This material was prepared for gluing by soaking in concentrated sulfuric acid (H_2SO_4) for three minutes and washing with hot water. When the strapping was thoroughly dry it was then wire brushed and cut to 50 inch lengths. Immediately prior to gluing the reinforcing material was thoroughly cleaned with acetone and wiped with a clean cloth.

Two adhesives were used in this study. Wood to wood bonds were accomplished with a room-temperature-setting resorcinol-phenol-resin (Cascophen RS-240 M-D and catalyst FM-124 D). Wood to metal bonds were made with an epoxy resin formulation (EPOX (R) 907 A-B). This epoxy formulation was used since it cured rapidly to high tensile-shear strengths and it was said to have the special property of good adhesion even to surfaces which have not been specially cleaned.

Laminating the wood to wood bonds was done using a pressure of approximately 190 pounds per square inch at 72 degrees F. Laminating the wood to metal bonds was accomplished with a pressure of ten pounds per square inch at approximately 75 degrees F. Self-centering type laminating clamps were used for all assemblies. Preliminary pressure was applied by tightening with an impact wrench.

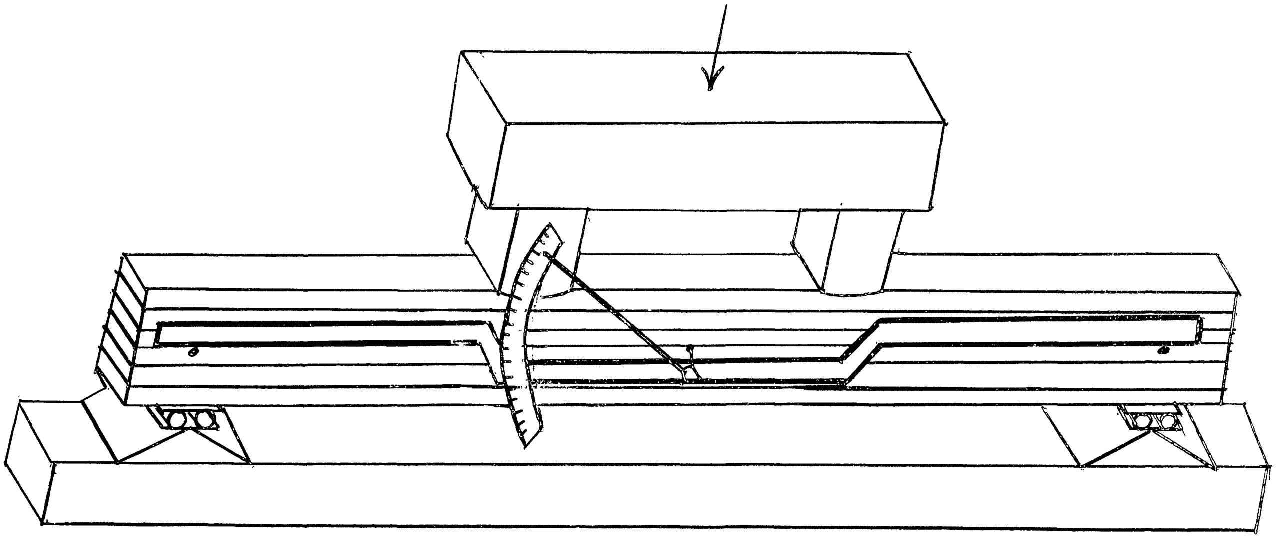
All wood to wood bonds were constructed during the same time interval to minimize variation. The laminations were double-spread on a mechanical spreader at a rate of at least 80 pounds of resin per 1,000 square feet of glue-joint area. The clamp spacing was six inches center to center, and one-half inch wood cauls were used. These beams remained in the clamps for a period of forty-eight hours and were thereafter allowed to set for a period of one week.

All epoxy resin glue lines were constructed during the same time interval. The laminations of the epoxy control beams were double spread with application of the resin by use of a wooden spatula. Laminating the reinforced beams was accomplished by spreading the epoxy resin on both surfaces of the metal strapping and on those surfaces of the wood which were to be in contact with the metal. Application of the resin was by use of a wooden spatula. Spread rate was difficult to control because of the heavy consistency of the epoxy, but calculations and test sample measurements indicated that approximately a 90 pound per 1,000 square feet of glue joint area spread rate was achieved. The epoxy resin bonded beams were placed in clamps having a spacing of three inches center to center and one-half inch wood cauls were used. These beams remained in clamps for a period of 24 hours before being removed. Following this, beams were placed in the testing laboratory for a period of at least three days prior to testing to allow the temperature of the beams to equal the temperature of the laboratory before testing.

The epoxy control beams were fabricated to determine whether the epoxy adhesive provided any degree of stiffening or strengthening of the beams. The resorcinol-phenol control beams were made to provide a basis of comparison for the epoxy control and the reinforced beams.

II. TESTING PROCEDURE

Static bending tests were conducted to determine the modulus of rupture, modulus of elasticity, and fiber stress at the proportional limit for all the experimental beams. The apparatus used for static bending is illustrated in Figure 2.



FIRGURE II. APPARATUS USED FOR TESTING EXPERIMENTAL BEAMS IN STATIC BENDING

Earlier investigators found that, "...when the length of a beam is less than 10 times its depth, failure will occur by shear, whereas, if it is more than 10 times the depth, failure will occur from bending."[1] According to this a span-depth ratio of thirteen was selected for use as it presumed to safely minimize danger of shear failure without engendering excessive length.

A 30,000 pound capacity Tinius Olson Universal testing machine was used. All beams were loaded at third-points with a rate of movement of the movable cross head of 0.14 inches per minute, determined by the formula.[2]

$$n = \frac{Z\,l^2}{5.4\,d}$$

in which:

n = rate of movement, inches per minute

Z = rate of fiber strain per inch of fiber length, inches per minute (Z = 0.0015 for bending small beams).

l = span of beam, inches

d = depth of beam, inches

The radius of curvature of the bearing blocks was determined in accordance with the American Society for Testing Materials specification D198-27. It states, that "...when testing beams under third-point loading on a span equal to 14 times the beam depth the load shall be applied through bearing blocks extending entirely across the face of the beam and having a radius of curvature three times the depth of the beam for a chord lenth at least equal to the depth of the beam. ...for span-depth ratios less than 14, the radius of curvature of the bearing blocks shall be proportionall increased..."[3] For

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[1] Charles Wilbur Leigh and John Frederic Mangold, Practical Mechanics and Strength of Materials (New York: McGraw-Hill Book Company, Inc., 1940), p. 323.

[2] Frederick F. Wangaard, The Mechanical Properties of Wood (New York: John Wiley and Sons, Inc., 1950), p. 285.

[3] American Society for Testing Materials, Committee D-7, ASTM Standards on Wood, Wood Preservatives and Related Materials, (Philadelphia: American Society for Testing Materials, 1954), p. 103

these tests the radius of curvature was calculated to be 9.69 inches.

Deflection of the beam was determined by use of a deflectometer attached at mid-height at the center of the span with respect to points at mid-height of the beam immediately above the supports (see Figure 2, page 7). The deflections were measured to the nearest 0.01 inch. The load was recorded to the nearest five pounds.

After failure had occurred each beam was removed from the machine; subsequently beams having failure typical for their respective groups were photographed (see Figures 3 through 11).

Immediately after failure, moisture content determinations were made by use of a portable moisture meter applied to the area of the failure. The moisture meter was repeadedly checked by comparing readings of the moisture meter with values determined by calculation of moisture content on an oven-dry basis. The moisture content at time of testing ranged from 6.5 to 8.5 per cent with an average of 7.6 per cent. Since the moisture content range was quite small and variations were distributed randomly throughout, it was decided that there would be no need to correct the strength properties to a constant moisture content.

III. COMPUTATIONS FOR MODULUS OF RUPTURE AND MODULUS OF ELASTICITY

The formula used to calculate the modulus of rupture is:

$$\text{MOR} = \frac{Pl}{bd^2}$$

in which:

MOR = modulus of rupture, pounds per square inch

P = maximum load, pounds

l = length of span, inches

b = width of beam, inches

d = depth of beam, inches

The preceeding formula was derived from the basic flexure formula:

$$S = \frac{Mc}{I}$$

in which:

S = the fiber stress in bending

M = the external moment, pound-inches

c = one-half the depth of the beam, inches

I = the moment of inertia of the section, inches^4

The formula used to determine the modulus of elasticity for third-point loading is:

$$E = \frac{Pl^3}{4.7\ ybd^3}$$

in which:

E = modulus of elasticity, pounds per square inch

P = load at proportional limit, pounds

l = length of span, inches

y = deflection at proportional limit, inches

b = width of the beam, inches

d = depth of the beam, inches

The preceeding formula was derived from the standard moment-area deflection formula:

$$E = \frac{\bar{x}A}{Iy}$$

in which:

E = modulus of elasticity, pounds per square inch

$\bar{x}$ = the length of the moment arm from the left side of the moment diagram to the center of gravity at the point of maximum deflection, inches

A = the area under the moment diagram from the left edge to the point of maximum deflection, pound-inches^2

I = moment of inertia of the section, inches^4

y = deflection, inches

CHAPTER III

RESULTS AND DISCUSSION

I. RESULTS

The mean modulus of rupture and mean modulus of elasticity value (see Table 1, page 13) for each treatment was compared with every other treatment by use of Duncan's multiple range test at the 95 per cent level of confidence.

Results from these statistical analyses of the modulus of rupture means indicate that: (see Table 8, page 30)

1. Those beams which were reinforced in both the top and bottom glue lines had a significantly larger modlulus of rupture than all other treatments except for those beams which were reinforced throughout every glue line and those beams which were reinforced in the bottom glue line only.
2. Those beams which were reinforce throughout every glue line had a significantly larger modulus of rupture than all other treatments except for those beams which were reinforced in the bottom glue line only.
3. Those beams which were reinforced in the bottom glue line only had a significantly larger modulus of rupture than the epoxy control beams, type D.
4. Upon comparing the remaining modulus of rupture means it was found that no other treatment was significantly better than any other treatment at the 95 per cent level of confidence.

Results from the statistical analyses of the modulus of elasticity means indicate that: (see Table 10, page 32)

1. Those beams which were reinforced throughout every glue line had a significantly larger modulus of elasticity than all other treatments

TABLE I - MEAN VALUES OF MOISTURE CONTENT MODULUS OF RUPTURE AND MODULUS OF ELASTICITY

Treatment	Type	Ave. M.C.	Modulus of Rupture	Modulus of Elasticity
Reinforced	A	7.5	11,166	1,896,678
	B	8.1	12,936	2,046,175
	C	7.5	14,404	2,135,778
	C	8.1	13,893	2,264,966
Epoxy Control	A	7.3	11,433	1,737,374
	B	7.4	11,218	1,792,004
	C	7.4	10,764	1,745,949
	D	7.7	10,499	1,630,327
Resorcinol-Phenol Control		7.6	11,577	1,728,980

except of those beams which were reinforced in the top and bottom glue lines and those beams which were reinforced in the bottom glue line only.

2. Those beams which were reinforced in the top and bottom glue lines had a significantly larger modulus of elasticity than all other treatments except of those beams which were reinforced in the bottom glue line only and those beams which were reinforced in the top glue line only.
3. Those beams which were reinforced in the bottom glue line only had a significantly larger modulus of elasticity than all remaining treatments except of those beams which were reinforced in the top glue line only.
4. Upon comparing all remaining modulus of elasticity means it was found that no other treatment was significantly larger than any other treatment at the 95 per cent level of confidence.

II. DISCUSSION

There was no significant difference between the modulus of rupture or modulus of elasticity means of the epoxy control and resorcinol-phenol control beams. The significant differences in the modulus of rupture and modulus of elasticity values resulting from the anlysis were therefore considered to be due to the reinforcing material and its placement within the wood beams.

A problem which arose while testing the experimental beams was that of horizontal shear failure. The amount of horizontal shear failure increased with the amount of reinforcing. Of the fifty control beams, 2 per cent failed in horizontal shear as compared to 20 per cent of the reinforced, type A; 30 per cent of the reinforced, type B; 40 per cent of the reinforced, type C; and 70 per cent of the reinforced, type D. The most probable explanation of this problem is that the increased amount of reinforcing material within the beams increased the stiffness as indicated by the mean modulus of elasticity values. In addition, the mean modulus of rupture values of the reinforced beams were greater than those of the non-reinforced beams. Due to the increase in stiffness sufficient deflection was not attained to cause excessive elongation of the fibers on the tension surface nor excessive crushing of the fibers on the compression surface which would cause tension or compression failure respectively. This, plus the fact that greater loads were applied to the reinforced beams, indicates that greater stresses occurred in the center portion of these beams. It is the author's belief that the magnitude of these stresses increased with the degree of reinforcement. Because wood is weaker in horizontal shear than in compression or tension parallel-to-grain, the occurrence of horizontal shear failure increased with the degree of reinforcement in a manner similar to that which would have occurred had the span-depth ratio been unfavorable.

The typical character of failure associated with each group of beams is important to note since it more completely describes the behavior of reinforced wood beams tested to failure at third points (see Figures 3 through 11, pages 33 to 41).

1. The failure occurring in the reinforced beams, types A and C, was mainly a tension failure in the bottom laminae (see Figures 3 and 5, page 33 and 35).
2. The failure occurring in the reinforced beams, type B, was mainly a tension failure extending through the bottom laminae with horizontal shear occurring immediately below the steel strapping (see Figure 4, page 34).
3. The failure occurring in the reinforced beams, type D, was mainly a horizontal shear failure occurring at mid-depth and extending

laterally at least one-half the length of the beam (see Figure 6, page 36).

4. The failure occurring in the epoxy control beams and resorcinol-phenol control beams was mainly a tension failure (see Figures 7 through 11, pages 37 through 41). There was no indication that the type of failure in the epoxy control beams was influenced by the presence of the epoxy glue lines.

The glue bond between the wood and metal was very effective since in those beams in which horizontal shear was critical there was almost complete wood failure. There was no indication that the epoxy resin formulation used in this study exhibited brittle properties.

The advantages of using this epoxy resin formulation were its ability to bond dissimilar materials, achieving good adhesion to surfaces which have not been specially cleaned and resulting in a rapid cure to high tensile and shear strength.

Disadvantages of using this two-part epoxy resin formulation include the necessary handling precautions to prevent contact with the skin, the limited pot life, the high viscosity, and the difficulty encountered in cleaning the laminating equipment. Another disadvantage is the cost of epoxy adhesives compared to the cost of more conventional adhesives used by the wood laminating industry. Since formulations and variations of this adhesive family are numerous and changes are relatively frequent, these "disadvantages" should be reviewed at any future date of anticipated use and not taken as categorical limitations of future use.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

I. CONCLUSIONS

Advantages obtained from reinforcing wood laminated beams as compared to the conventional resorcinol-phenol control beams are:

1. Significantly higher strength by reinforcing every glue line or the top and bottom glue lines.
2. Significantly greater stiffness by reinforcing every glue line, the top and bottom glue lines, or the bottom glue line only.

In reinforcing wooden beams with steel strapping, the most desirable location of the reinforcing material would appear to be close to the tension and compression surfaces. This would be more economical than reinforcing every glue line. Though the mean modulus of elasticity for those beams reinforced in the top and bottom glue lines was not the largest, there was no significant difference between their mean and the largest mean.

II. RECOMMENDATIONS

It is reasonable to believe that with further investigations a lower cost adhesive may be used to bond the reinforcing material to the wood with good results.

It also seems possible that other materials, such as different forms of metal (wire strands or rods), fiberglass, or high tensile strength plastic could be suitably used for the reinforcement of wood beams.

These materials and materials similar to that used in this study should also be investigated to determine the possiblity of pre-stressing the reinforcing material prior to gluing. It is reasonable to believe that the pre-stressed material would impart the most favorable strength properties to the beam if placed in the lower portion of the beam since initial compressive stresses would tend to decrease the magnitude of the tension stresses for a given load, hence, the beam would be able to support greater loads.

Other important areas for investigation should include studies concerned with development of special equipment to handle and apply the reinforcing material and adhesives, and further explore applications of the principles of reinforcing.

Although the general application of reinforced wooden beams may not be economically feasible at present, limited application may be found in particular cases where rigid standards of strength and/or stiffness are required. With future developments of newer and more suitable adhesive formulations and with improved laminating techniques, reinforcement of laminated wooden beams should become an important adjunct to many wood using enterprises.

CHAPTER V

SUMMARY

An investigation was conducted to determine if there would be a significant increase in strength and stiffness achieved by reinforcing wood laminated beams with steel strapping. Should there be significant increase in strength and stiffness, this study was to ascertain in what portions of the wood beam this reinforcement would be most significantly effective.

This study entailed the use of horizontally laminated Douglas-fir test beams. Each beam was fabricated with six wood laminae and in the case of the reinforced beams high tensile strength steel strapping was placed in different combinations of glue lines.

An epoxy resin formulation was used to bond the wood to the metal. A resorcinol-phenol adhesive was used to bond the wood to wood.

Ninety experimental beams were constructed. Forty beams were reinforced, forty beams were used as the epoxy control, and ten beams were used as the resorcinol-phenol control. Reinforcing material was placed in four different combinations in the reinforced beams.

The experimental beams were tested to ultimate failure in static bending by using A.S.T.M. standard testing procedures.

The data obtained from testing the experimental beams was used to determine the modulus of rupture and modulus of elasticity. These calculations were then statistically analyzed using the analysis of variance and Duncan's multiple range test at the 95 per cent level of confidence.

The results obtained from the statistical analyses indicated that the types of reinforced beams which had a significantly greater modulus of rupture than the control beams were those which were reinforced in every glue line and those reinforced in the top and bottom glue lines only. It was also found that the types of reinforced beams which had a significantly greater modulus of elasticity than the control beams were those which were reinforced in every glue line, in the top and bottom glue lines, and in the bottom glue line only.

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APPENDIX A

TABLES OF DATA
ANALYSIS

LIST OF SYMBOLS

M.O.R. = Modulus of rupture

M.O.E. = Modulus of elasticity

RA = Reinforced in the top glue line of the beam only

RB = Reinforced in the bottom glue line of the beam only

RC = Reinforced in the top and bottom glue lines of the beam

RD = Reinforced throughout every glue line of the beam

EA = Epoxy control with epoxy in top glue line of the beam only

EB = Epoxy control with epoxy in bottom glue line of the beam only

EC = Epoxy control with epoxy in top and bottom glue lines of the beam

ED = Epoxy control with epoxy in every glue line of the beam

C = Resorcinol-phenol control beams

SSR = Significant studentized range for the 5 per cent level of confidence

LSR = Least significant range

P = The number of means involved

d.f. = Degrees of freedom

TABLE II - M.O.R. (x) VALUES FOR THE REINFORCED BEAMS

A		B	
X	X^2	X	X^2
12,662	160,326,244	10,366	107,453,956
11,768	138,485,825	13,101	171,636,201
10,873	118,222,129	13,118	172,081,924
11,886	141,276,996	12,764	162,919,696
8,087	65,399,569	13,422	180,150,084
7,901	62,425,801	11,210	125,462,401
14,013	196,364,169	14,722	216,737,284
10,029	100,580,841	15,144	229,340,736
13,912	193,543,744	12,578	158,206,084
10,535	110,986,225	12,936	167,340,096

A:

Total - 111,666
Total^2 - 12,469,295,556
$\Sigma(X^2)$ - 1,287,611,543

B:

Total - 129,361
Total^2 - 16,734,268,321
$\Sigma(X^2)$ - 1,691,328,462

C		D	
X	X^2	X	X^2
14,126	199,543,876	12,001	144,024,001
15,550	241,802,500	15,091	227,738,281
13,911	193,515,921	14,641	214,358,881
14,904	222,129,216	13,041	170,067,681
10,930	119,464,900	14,361	206,238,321
17,438	304,083,844	15,572	242,487,184
15,782	249,071,524	14,004	196,112,016
15,865	251,698,225	15,805	249,798,025
13,282	176,411,524	13,579	184,389,241
12,255	150,185,025	10,837	117,440,569

C:

Total - 144,043
Total^2 - 20,748,385,849
$\Sigma(X^2)$ - 2,107,906,555

D:

Total - 138,932
Total^2 - 19,302,100,624
$\Sigma(X^2)$ - 1,952,654,200

TABLE III - M.O.R. (X) VALUES FOR THE EPOXY CONTROL BEAMS

A		B	
X	X^2	X	X^2
12,133	147,209,689	9,117	83,119,689
11,423	130,484,929	13,676	187,032,976
7,367	54,272,689	10,209	104,223,681
12,809	164,070,481	12,913	166,745,569
10,313	106,357,969	13,451	180,929,401
10,348	107,081,104	10,088	101,767,744
14,092	198,584,464	9,273	85,988,529
13,277	176,278,729	11,388	129,686,544
9,915	98,307,225	10,573	111,788,329
12,653	160,098,409	11,492	132,066,064

A:
Total - 114,330
Total^2 - 13,071,348,900
$\Sigma(X^2)$ - 1,342,745,688

B:
Total - 112,180
Total^2 - 12,584,352,400
$\Sigma(X^2)$ - 1,283,348,526

C		D	
X	X^2	X	X^2
10,972	120,384,784	15,253	232,654,009
8,979	80,622,441	5,720	32,718,400
12,185	148,474,225	9,117	83,119,689
10,643	113,273,449	11,301	127,712,601
14,213	202,009,369	13,087	171,269,569
14,127	199,572,129	10,833	117,353,889
6,431	41,357,761	6,084	37,015,056
9,741	94,887,081	9,949	98,982,601
7,817	61,105,489	11,717	137,288,089
12,532	157,051,024	11,925	142,205,625

C:
Total - 107,640
Total^2 - 11,586,369,600
$\Sigma(X^2)$ - 1,218,737,752

D:
Total - 104,986
Total^2 - 11,022,060,196
$\Sigma(X^2)$ - 1,180,319,528

TABLE IV - M.O.R. (X) AND M.O.E. (X) VALUES FOR THE RESORCINOL-PHENOL CONTROL BEAMS

M.O.R. Values

X	X^2
12,168	148,060,224
10,435	108,889,225
12,099	146,385,801
13,000	169,000,000
8,788	77,228,944
13,884	192,765,456
10,729	115,111,441
11,128	123,832,384
14,577	212,488,929
8,961	80,299,521

Total - 115,769
Total^2 - 13,402,461,361
$\Sigma(X^2)$ - 1,374,061,925

M.O.E. Values

X	X^2
1,873,850	3,511,313,822,500
1,728,696	2,988,389,860,416
1,856,088	3,445,062,663,744
1,576,676	2,485,907,208,976
1,596,455	2,548,668,567,025
1,894,104	3,587,629,962,816
1,906,297	3,633,968,252,209
1,379,362	1,902,639,527,044
1,883,925	3,549,173,405,625
1,594,347	2,541,942,356,409

Total - 17,289,800
Total^2 - 298,937,184,040,000
$\Sigma(X^2)$ - 30,194,695,626,764

TABLE V - M.O.E. (X) VALUES FOR THE REINFORCED BEAMS

A		B	
X	X^2	X	X^2
1,695,481	2,874,655,821,361	2,045,894	4,185,682,259,236
2,081,112	4,331,027,156,544	2,226,216	4,956,037,678,656
1,977,076	3,908,829,509,776	2,032,971	4,132,971,086,841
1,690,696	2,858,452,964,416	2,246,650	5,047,436,222,500
1,440,965	2,076,380,131,225	2,310,840	5,339,981,505,600
1,647,536	2,714,374,871,296	1,923,941	3,701,548,971,481
2,056,936	4,230,985,708,096	2,042,828	4,173,146,237,584
1,980,720	3,923,251,718,400	2,056,936	4,230,985,708,096
2,112,852	4,464,143,573,904	1,529,302	2,338,764,607,204
2,283,403	5,213,929,260,409	2,046,175	4,186,832,130,625

Total - 18,966,777
Total^2 - 359,738,629,767,729
$\Sigma(X^2)$ - 36,596,030,715,427

Total - 20,461,753
Total^2 - 418,683,335,833,009
$\Sigma(X^2)$ - 42,293,386,407,823

C		D	
X	X^2	X	X^2
2,137,620	4,569,419,264,400	2,318,494	5,375,414,428,036
1,505,792	2,267,409,547,264	2,619,488	6,861,717,382,144
1,251,136	1,565,341,290,496	2,250,238	5,063,571,056,644
2,406,358	5,790,558,824,164	2,115,230	4,474,197,952,900
2,217,624	4,917,856,205,376	2,187,575	4,785,484,380,625
2,569,305	6,601,328,183,025	2,257,282	5,095 322,027,524
2,376,255	5,646,587,825,025	2,152,624	4,633,790,085,376
2,519,599	6,348,379,120,801	2,382,040	5,674,114,561,600
2,067,345	4,273,915,349,025	2,289,006	5,239,548,468,036
2,306,746	5,321,077,108,516	2,077,685	4,316,774,959,225

Total - 21,357,780
Total^2 - 456,154,766,528,400
$\Sigma(X^2)$ - 47,301,872,718,092

Total - 22,649,662
Total^2 - 513,007,188,714,244
$\Sigma(X^2)$ - 51,519,935,302,110

TABLE VI - M.O.E. (X) VALUES FOR THE EPOXY CONTROL BEAMS

A		B	
X	X^2	X	X^2
2,003,400	4,013,611,560,000	1,490,666	2,222,085,123,556
1,512,504	2,287,668,350,016	2,056,799	4,230,422,126,401
1,228,177	1,508,418,743,329	2,164,932	4,686,930,564,624
1,978,454	3,914,280,230,116	1,820,327	3,313,590,386,929
1,340,621	1,797,264,665,641	1,869,938	3,496,668,123,844
1,961,187	3,846,254,448,969	1,600,396	2,561,267,356,816
2,118,044	4,486,110,385,936	1,543,352	2,381,935,395,904
1,954,908	3,821,665,288,464	1,892,774	3,582,593,415,076
1,827,268	3,338,908,343,824	1,589,372	2,526,103,354,384
1,449,172	2,100,099,485,584	1,891,489	3,577,730,637,121

A:
Total - 17,373,735
Total^2 - 301,846,667,850,225
≤(X^2) - 31,114,281,501,879

B:
Total - 17,920,045
Total^2 - 321,129,012,802,025
≤(X^2) - 32,579,326,484,655

C		D	
X	X^2	X	X^2
1,848,663	3,417,554,887,569	1,973,040	3,892,886,841,600
1,489,026	2,217,198,428,676	1,606,852	2,581,973,349,904
1,761,784	3,103,882,862,656	1,778,751	3,163,955,120,001
1,780,666	3,170,771,403,556	1,508,679	2,276,112,325,041
1,541,714	2,376,882,057,796	1,738,960	3,023,981,881,600
2,084,039	4,343,218,553,521	1,492,134	2,226,463,873,956
1,649,895	2,722,153,511,025	1,447,389	2,094,934,917,321
1,815,256	3,295,154,345,536	1,587,111	2,518,921,326,321
1,816,331	3,299,058,301,561	1,529,928	2,340,679,685,184
1,672,117	2,795,975,261,689	1,640,423	2,690,987,618,929

C:
Total - 17,459,491
Total^2 - 304,833,825,979,081
≤(X^2) - 30,741,849,613,585

D:
Total - 16,303,267
Total^2 - 265,796,514,873,289
≤(X^2) - 26,810,896,939,857

TABLE VII - ANALYSIS OF VARIANCE[1] OF THE M.O.R. VALUES

Category	Sum-Squares	d. f.	Variance	Sample	F.05
Total	504,932,895.12	89			
Treatment	91,927,924.72	2	45,963,962.36	9.68	3.11*
Residual	413,004,970.40	87	4,747,183.57		

Total (X^2) - 13,438,714,179	Total R^2 - 274,578,096,004
Grand Total - 1,078,907	Total EC^2 - 192,840,426,496
Grand Total^2 - 1,164,040,314,649	Total C^2 - 13,402,461,361
Total $(X)^2$ - 130,920,642,807	

$$\text{Correction Factor} = \frac{\text{Grand Total}^2}{N}$$

$$\text{Total Sum Squares} = \Sigma(X^2) - \text{Correction Factor}$$

$$\text{Treatment Sum Squares} = \frac{\Sigma(TR)^2}{n} + \frac{\Sigma(T_{EC})^2}{n} + \frac{\Sigma(T_C)^2}{n} - \text{Correction Factor}$$

$$\text{Residual Sum Squares} = \text{Total Sum Squares} - \text{Treatment Sum Squares}$$

* Significant difference between effects

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[1] George W. Snedecor, *Calculation and Interpretation of Analysis of Variance and Covariance* (Ames, Iowa: Collegiate Press, Inc., 1934).

TABLE VIII - DUNCAN'S MULTIPLE-RANGE TEST[1] FOR COMPARISON OF THE M.O.R. MEANS

$$S_{\bar{x}} = \sqrt{\text{error variance/repetitions within each mean}} = 688.998$$

Value of P	2	3	4	5	6	7	8	9
SSR	2.815	2.965	3.065	3.13	3.19	3.23	3.27	3.30
LSR	1939.5	2042.9	2111.8	2156.6	2197.9	2225.5	2253.0	2273.7

Means in Order of Size	RC	RD	RB	C	EA	EB	RA	EC	ED
	14,404	13,893	12,936	11,577	11,433	11,218	11,167	10,764	10,499

RC-ED - 3,905 > 2,274*
RC-EC - 3,640 > 2,253*
RC-RA - 3,237 > 2,225*
RC-EB - 3,186 > 2,198*
RC-EA - 2,971 > 2,156*
RC-C - 2,827 > 2,112*
RC-RB - 1,468 < 2,042*
RC-RD - 511 < 1,939

RD-ED - 3,394 > 2,274*
RD-EC - 3,129 > 2,253*
RD-RA - 2,726 > 2,225*
RD-EB - 2,675 > 2,198*
RD-EA - 2,460 > 2,156*
RD-C - 2,316 > 2,112
RD-RB - 957 < 2,042

RB-ED - 2,437 > 2,274*
RB-EC - 2,172 < 2,253
RB-RA - 1,769 < 2,225
RB-EB - 1,718 < 2,198
RB-EA - 1,503 < 2,156
RB-C - 1,309 < 2,112

* Significant difference

All other differences between means are insignificant

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[1] Robert G. D. Steel and James H. Torrie, *Principles and Procedures of Statistics With Special Reference to the Biological Sciences* (New York: McGraw-Hill Book Company, Inc., 1960), p. 108.

TABLE IX - ANALYSIS OF VARIANCE[1] OF THE M.O.E. VALUES

Category	Sum Squares	d. f.	Variance	Sample	F.05
Total	8,863,022,099,790.89	89			
Treatment	2,863,636,796,854.59	2	1,431,818,398,427.295	20.64	3.11*
Residual	5,999,385,302,936.30	87	68,958,451,757.8885		

Total (X^2) - 329,152,275,310,192

Grant Total - 169,782,310

Grand $Total^2$ - 28,826,032,788,936,100

Total $(X)^2$ - 3,240,126,388,022

Total R^2 - 6,961,561,423,584,784

Total EC^2 - 4,768,805,440,545,444

Total C - 298,937,184,040,000

Correction Factor - $\frac{\text{Grand Total}^2}{N}$

Total Sum Squares - $\Sigma(X^2)$ - Correction Factor

Treatment Sum Squares - $\frac{\Sigma(T_R)^2}{n} \not- \frac{\Sigma(T_{EC})^2}{n} \not- \frac{\Sigma(T_C)^2}{n}$ - Correction Factor

Residual Sum Squares - Total Sum Squares - Treatment Sum Squares

* Significant difference between effects

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[1] Ibid.

TABLE X - DUNCAN'S MULTIPLE RANGE TEST[1] FOR COMPARISON OF THE M.O.E. MEANS

$$S_{\bar{x}} = \sqrt{\frac{\text{error variance}}{\text{repetitions within each mean}}} = 83,041.225$$

Value of P	2	3	4	5	6	7	8	9.
SSR	2.815	2.965	3.065	3.13	3.19	3.23	3.27	3.30
LSR	233,761	246,217	254,521	259,919	264,902	268,223	271,545	274,036

Means in Order of Size	RD	RC	RB	RA	
	2,264,966	2,135,778	2,046,175	1,896,678	
	EB	EC	EA	C	ED
	1,792,004	1,745,949	1,737,374	1,728,980	1,630,327

RD-ED - 634,640 > 274,036*
RD-C - 535,986 > 271,545*
RD-EA - 527,593 > 268,223*
RD-EC - 519,017 > 264,902*
RD-EB - 472,962 > 259,919*
RD-RA - 368,288 > 254,521*
RD-RB - 218,791 < 246,217
RD-RC - 129,188 < 233,761

RB-ED - 415,849 > 274,036*
RB-C - 317,195 > 271,545*
RB-EA - 308,802 > 268,223*
RB-EC - 300,226 > 264,902*
RB-EB - 254,171 < 259,919
RB-RA - 149,498 < 254,521

RC-ED - 505,451 > 274,036*
RC-C - 406,798 > 271,545*
RC-EA - 398,404 > 268,223*
RC-EC - 389,829 > 264,902*
RC-EB - 343,774 > 259,919*
RC-RA - 239,100 < 254,521
RC-RB - 89,603 < 246,217

* Significant difference

All other differences between means are insignificant

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[1] Ibid.

APPENDIX B

PHOTOGRAPHS OF TYPICAL FAILURES

FIGURE III TYPICAL FAILURE OF THE REINFORCED BEAMS, TYPE A

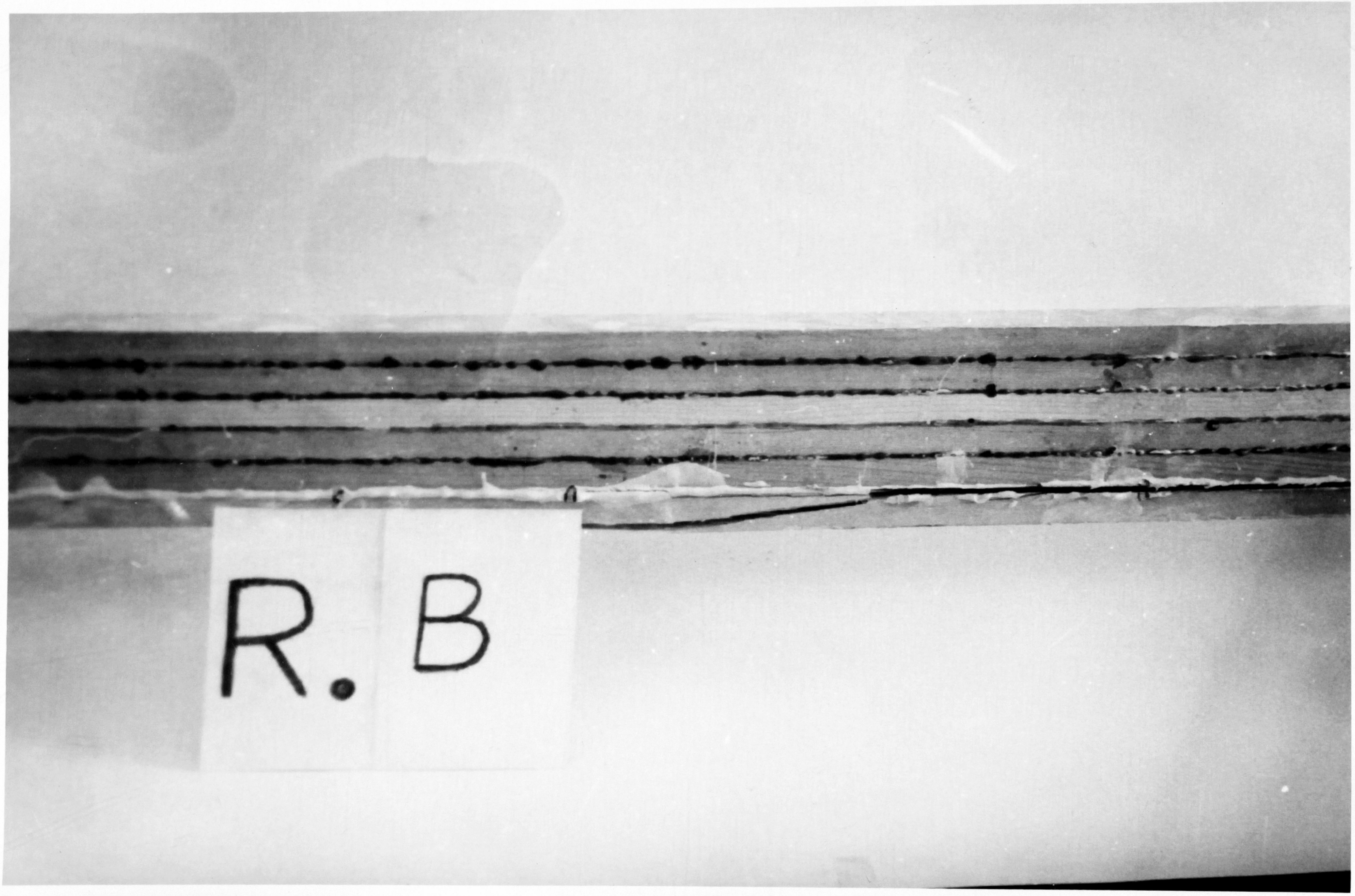


FIGURE IV TYPICAL FAILURE OF THE REINFORCED BEAMS, TYPE B

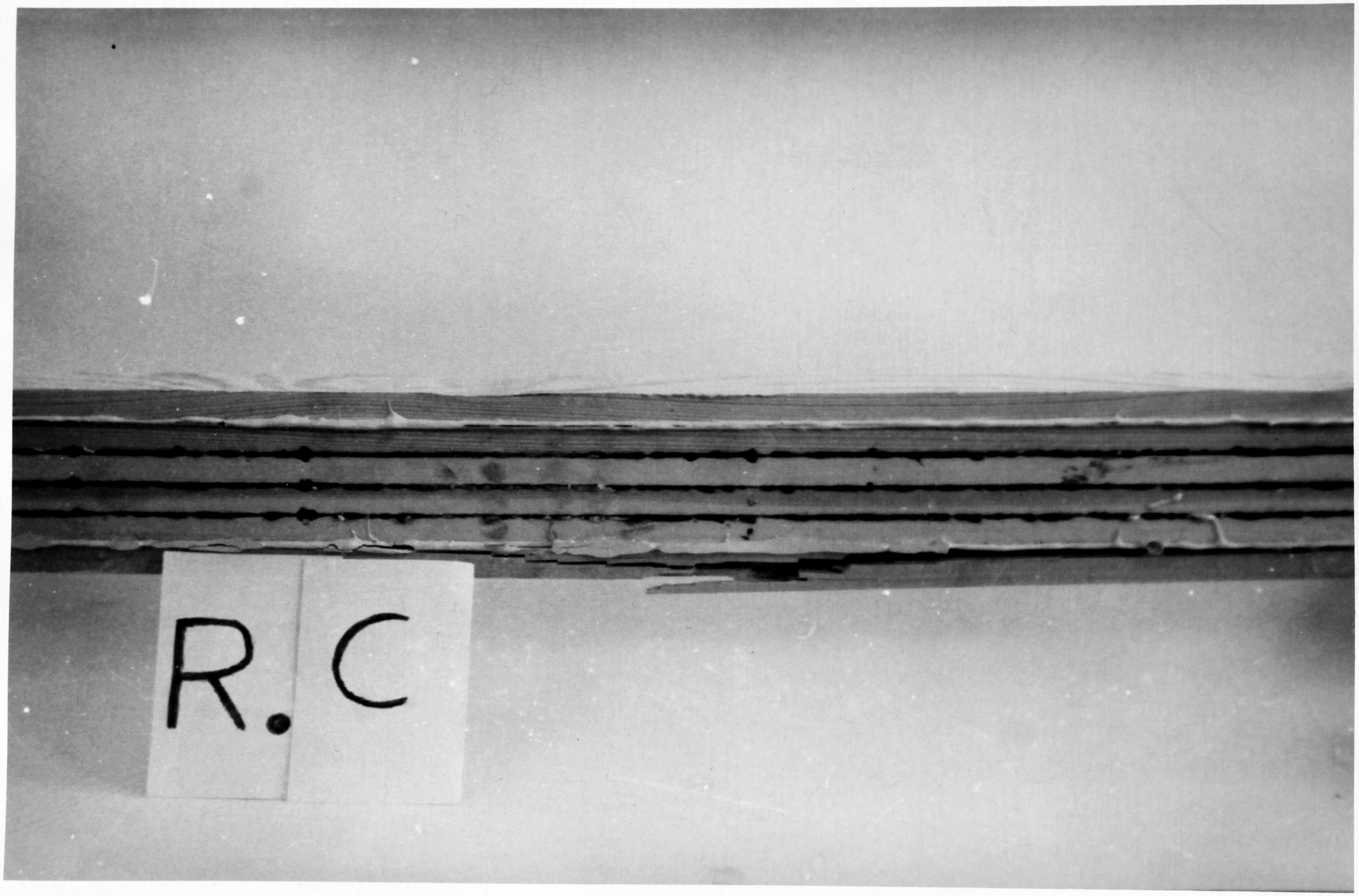


FIGURE V TYPICAL FAILURE OF THE REINFORCED BEAMS, TYPE C

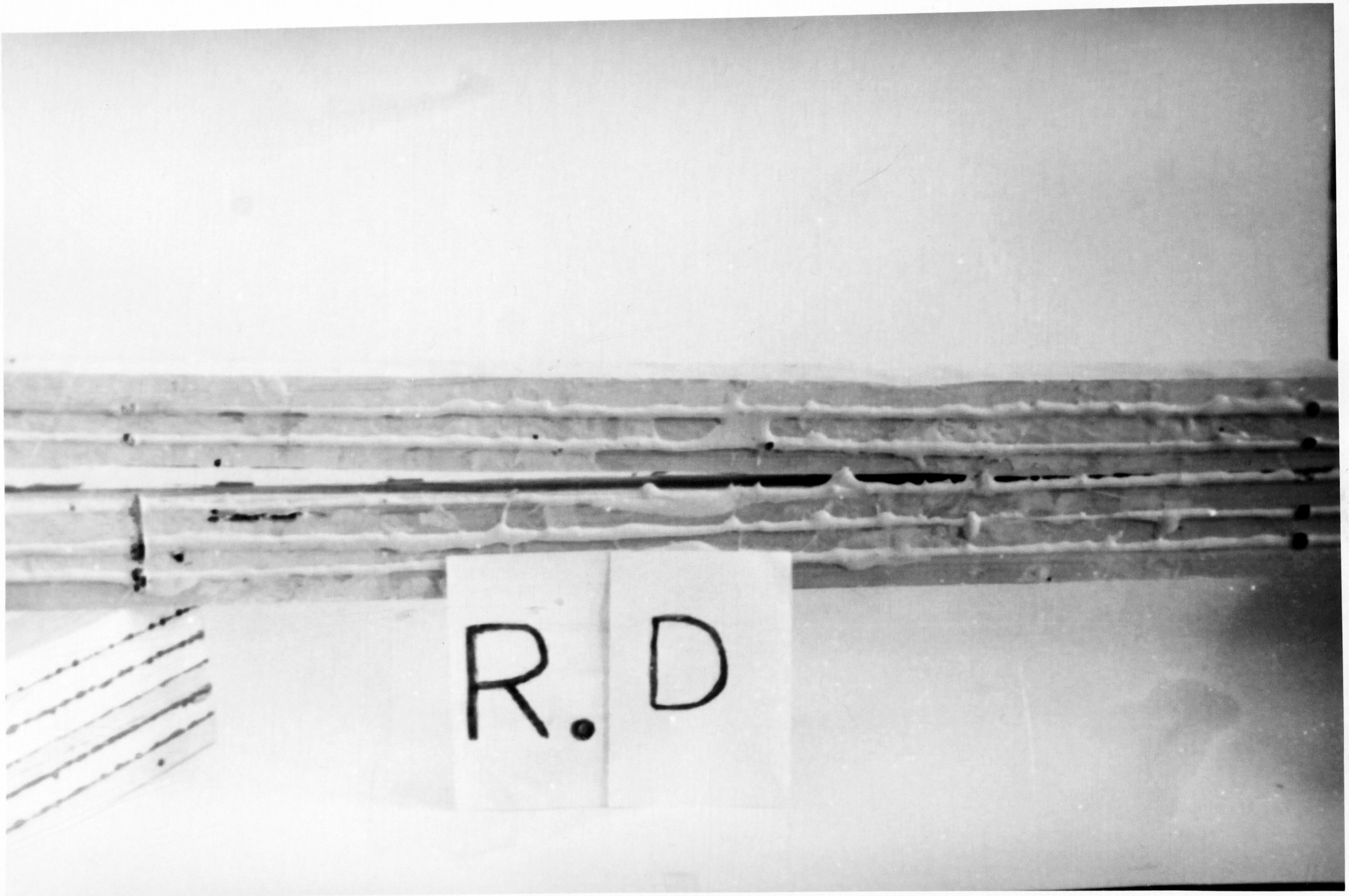


FIGURE VI   TYPICAL FAILURE OF THE REINFORCED BEAMS, TYPE D

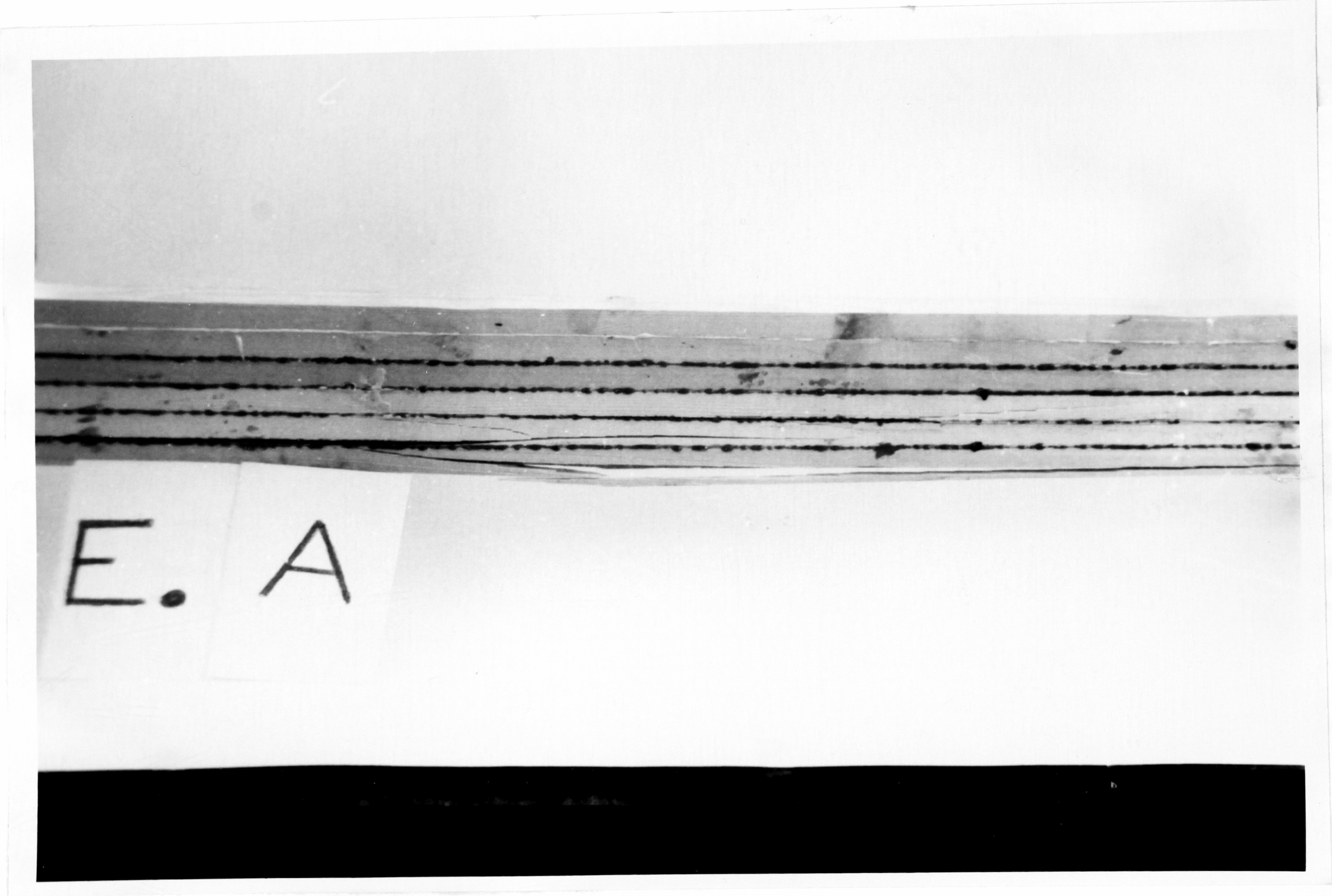


FIGURE VII   TYPICAL FAILURE OF THE EPOXY CONTROL BEAMS, TYPE A

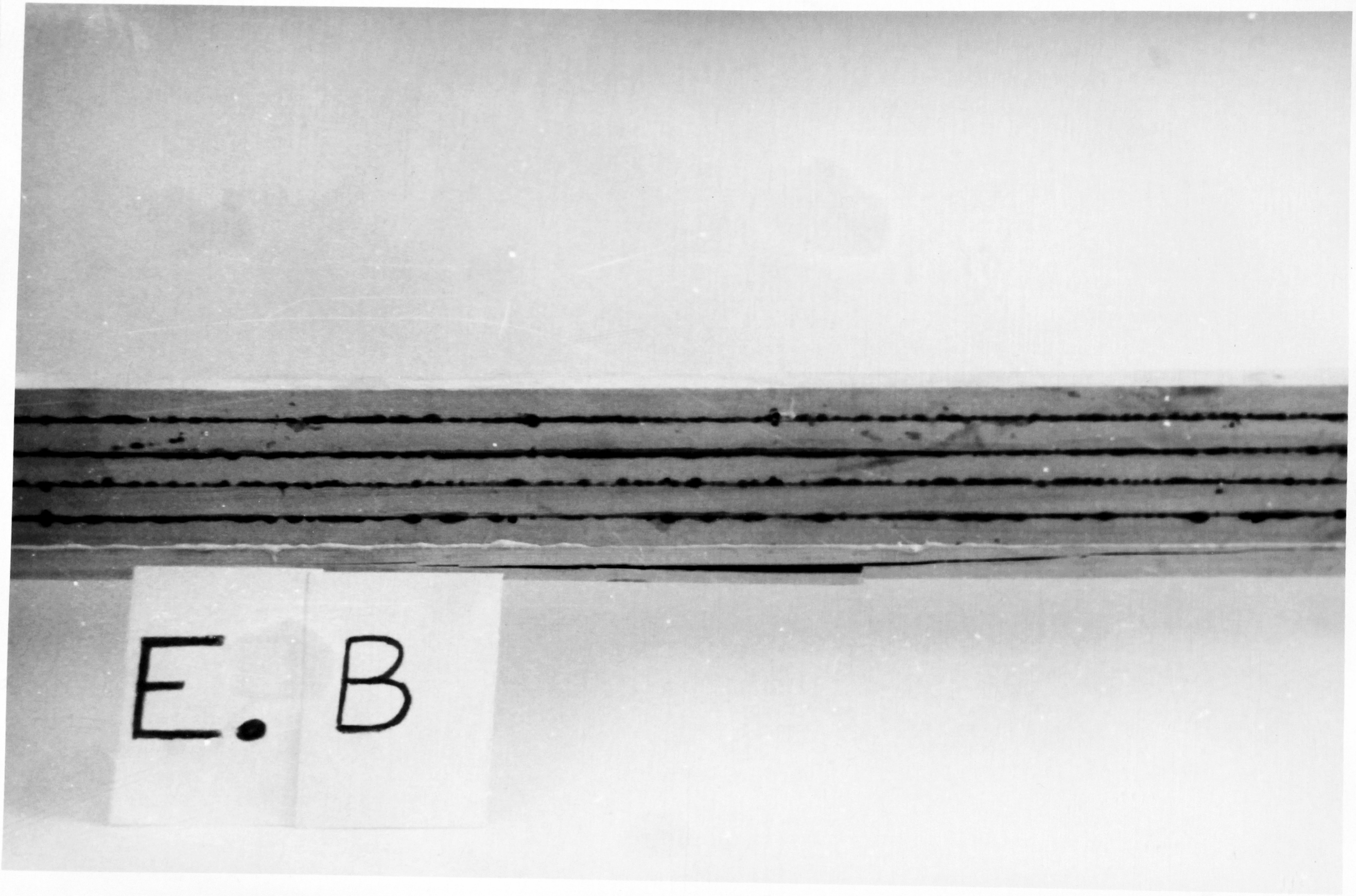


FIGURE VIII   TYPICAL FAILURE OF THE EPOXY CONTROL BEAMS, TYPE B

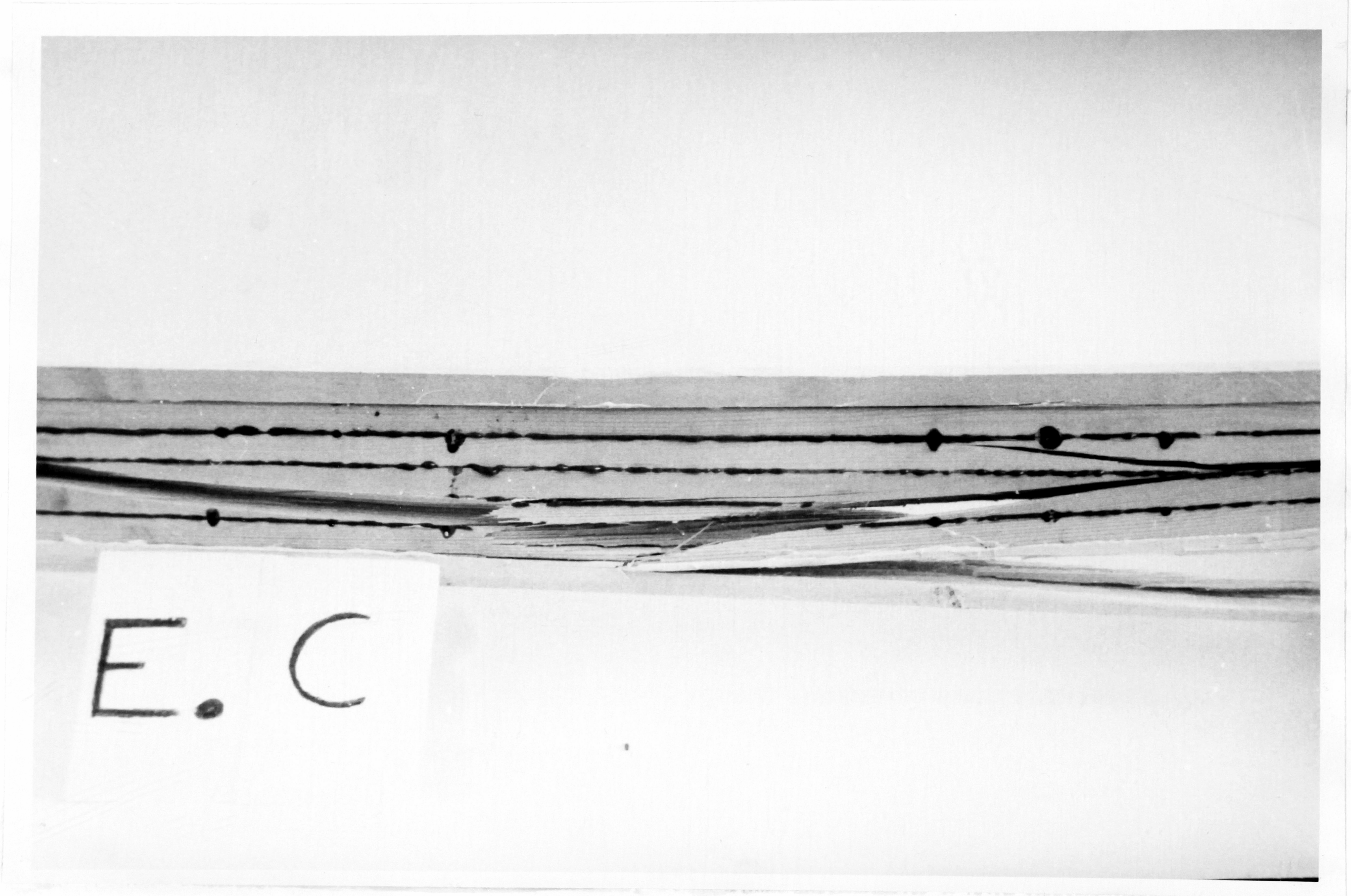


FIGURE IX   TYPICAL FAILURE OF THE EPOXY CONTROL BEAMS, TYPE C

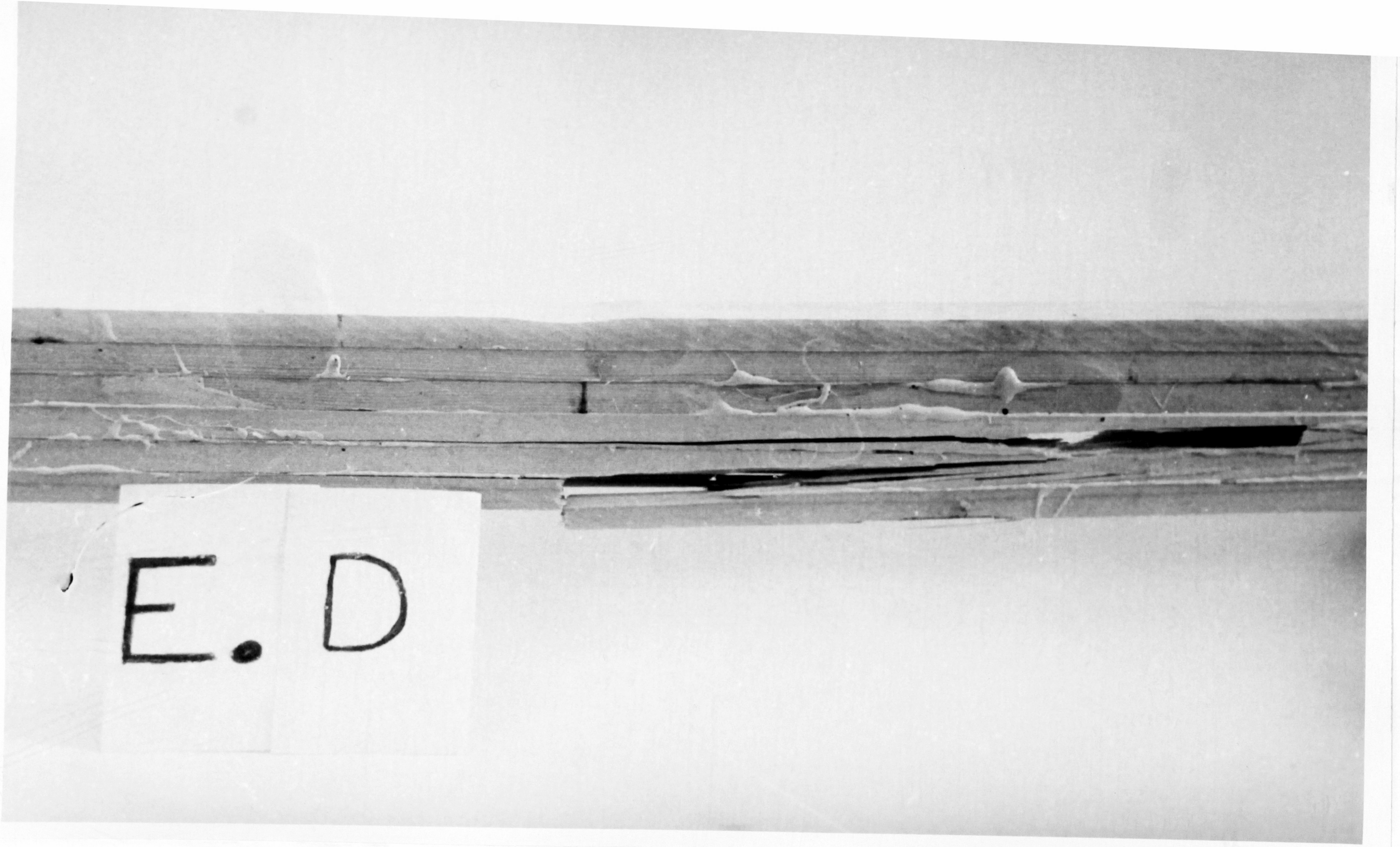


FIGURE X   TYPICAL FAILURE OF THE EPOXY CONTROL BEAMS TYPE D

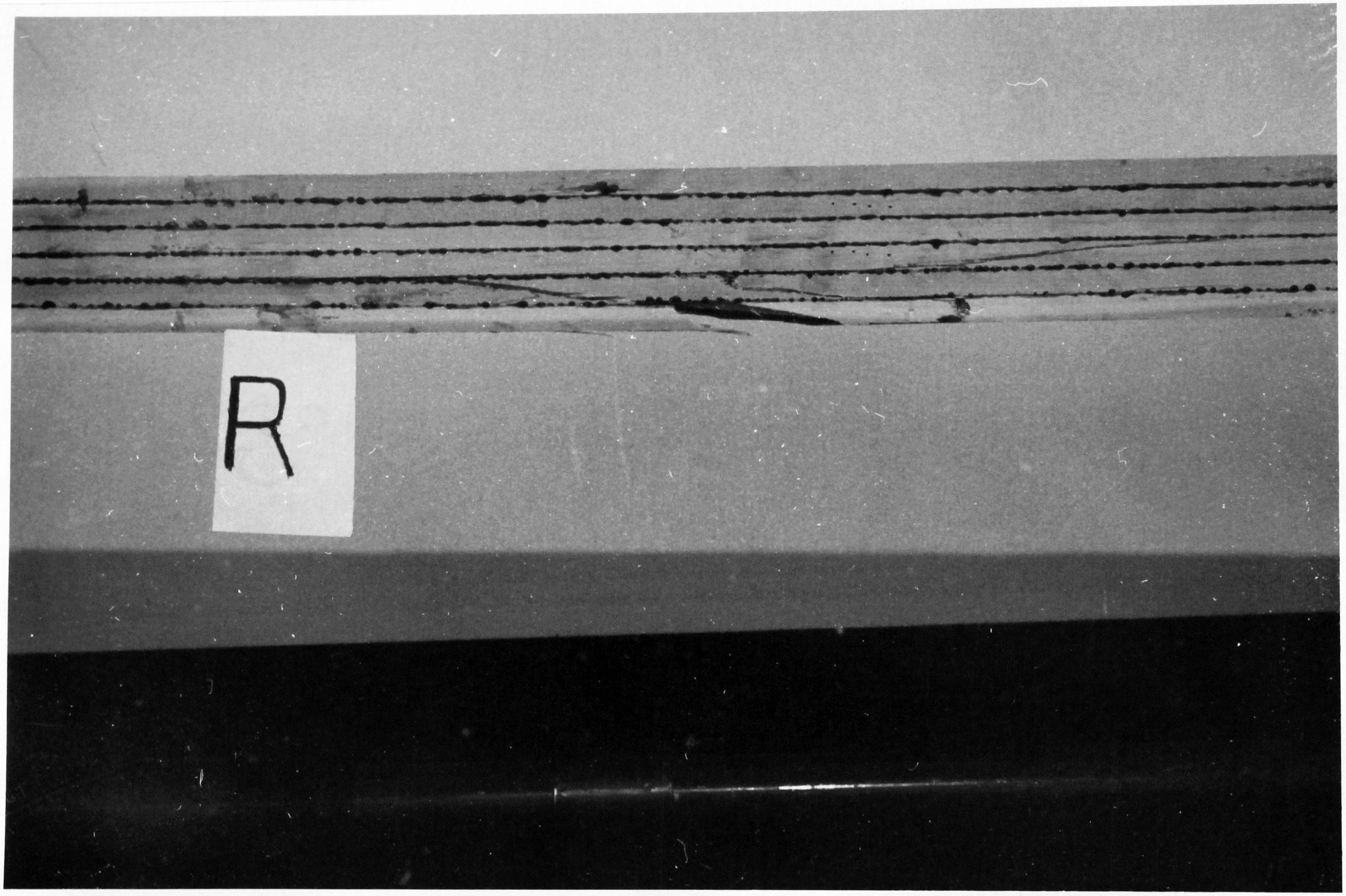


FIGURE XI TYPICAL FAILURE OF THE RESORCINOL-PHENOL CONTROL BEAMS

APPENDIX C

STRESS-STRAIN DIAGRAMS

FIGURE [illegible]

STRESS-STRAIN DIAGRAM OF AVERAGES OF THE DATA OBTAINED FROM
THE REINFORCED BEAMS, TYPE A

Ave. Max. Load 3307.0 lb.
Ave. Def. at Max. Load 0.654 in.
Ave. Load at P.L. 2585.0 lb.
Ave. Def. at P.L. 0.497 in.

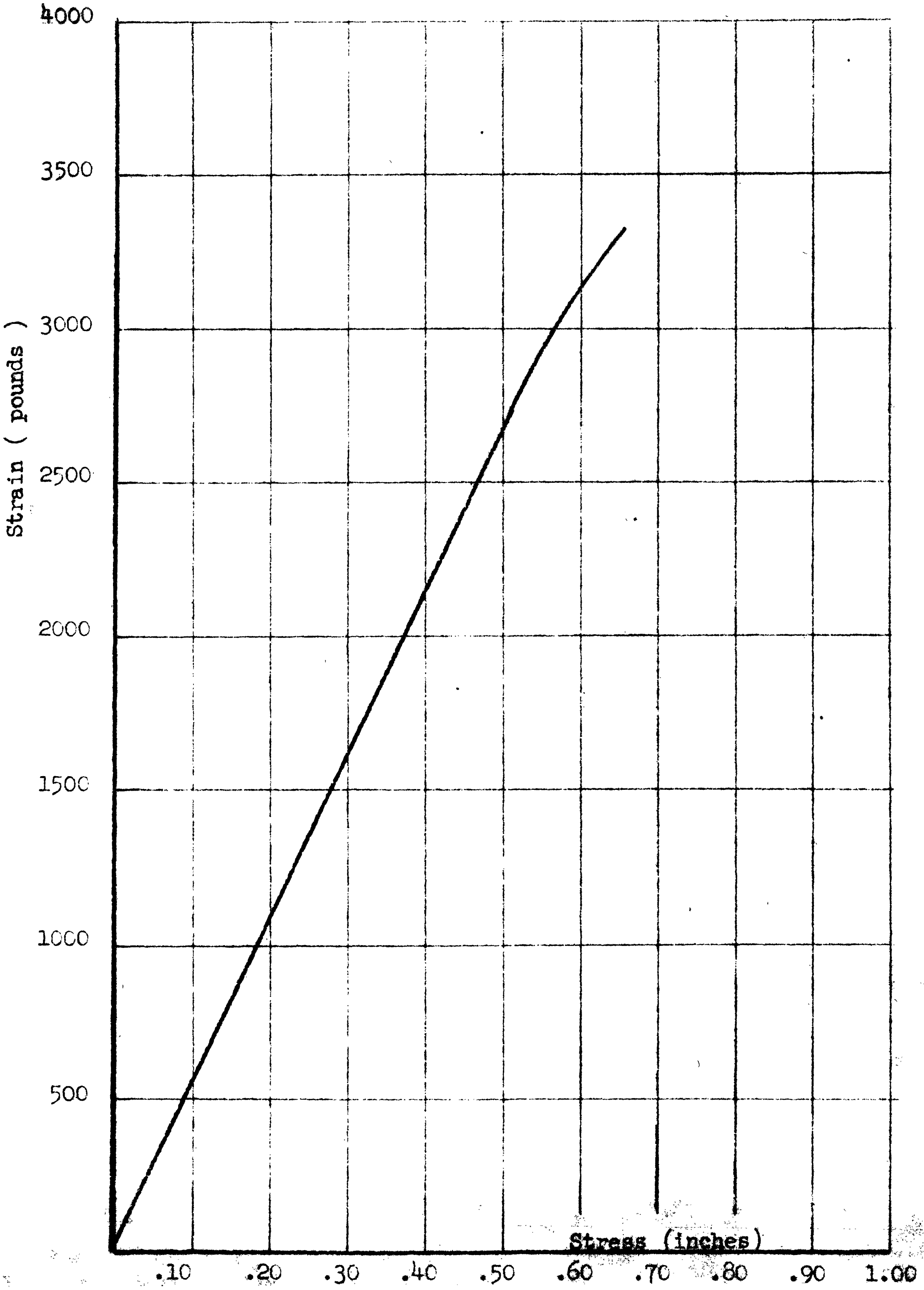


FIGURE XIII

STRESS-STRAIN DIAGRAM OF AVERAGES OF THE DATA OBTAINED FROM THE REINFORCED BEAMS, TYPE B

Ave. Max. Load 3831.1 lb.

Ave. Def. at Max. Load 0.872 in.

Ave. Load at P.L. 2486.7 lb.

Ave. Def. at P.L. 0.442 in.

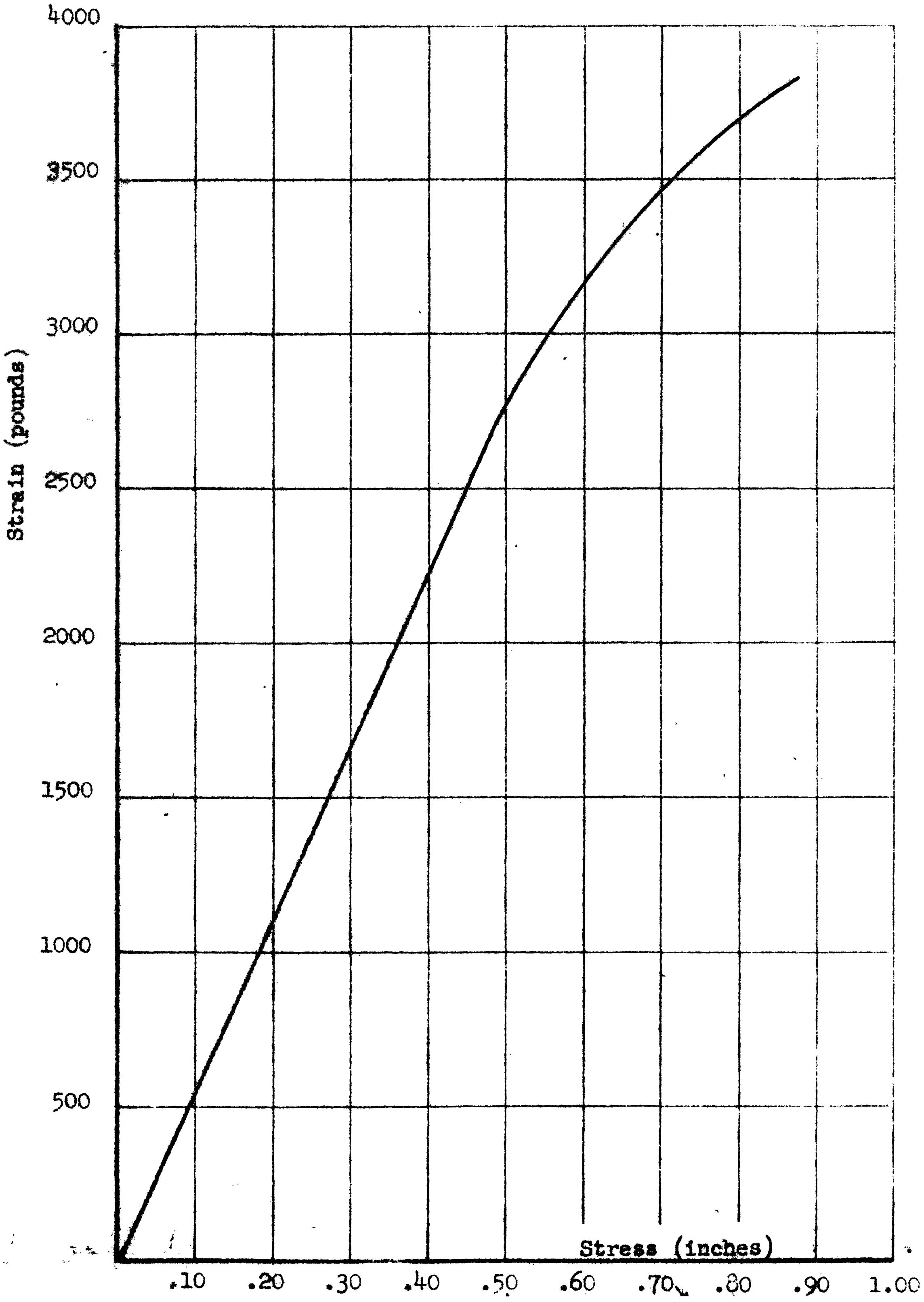


FIGURE XIV

STRESS-STRAIN DIAGRAM OF AVERAGES OF THE DATA OBTAINED FROM
THE REINFORCED BEAMS, TYPE C

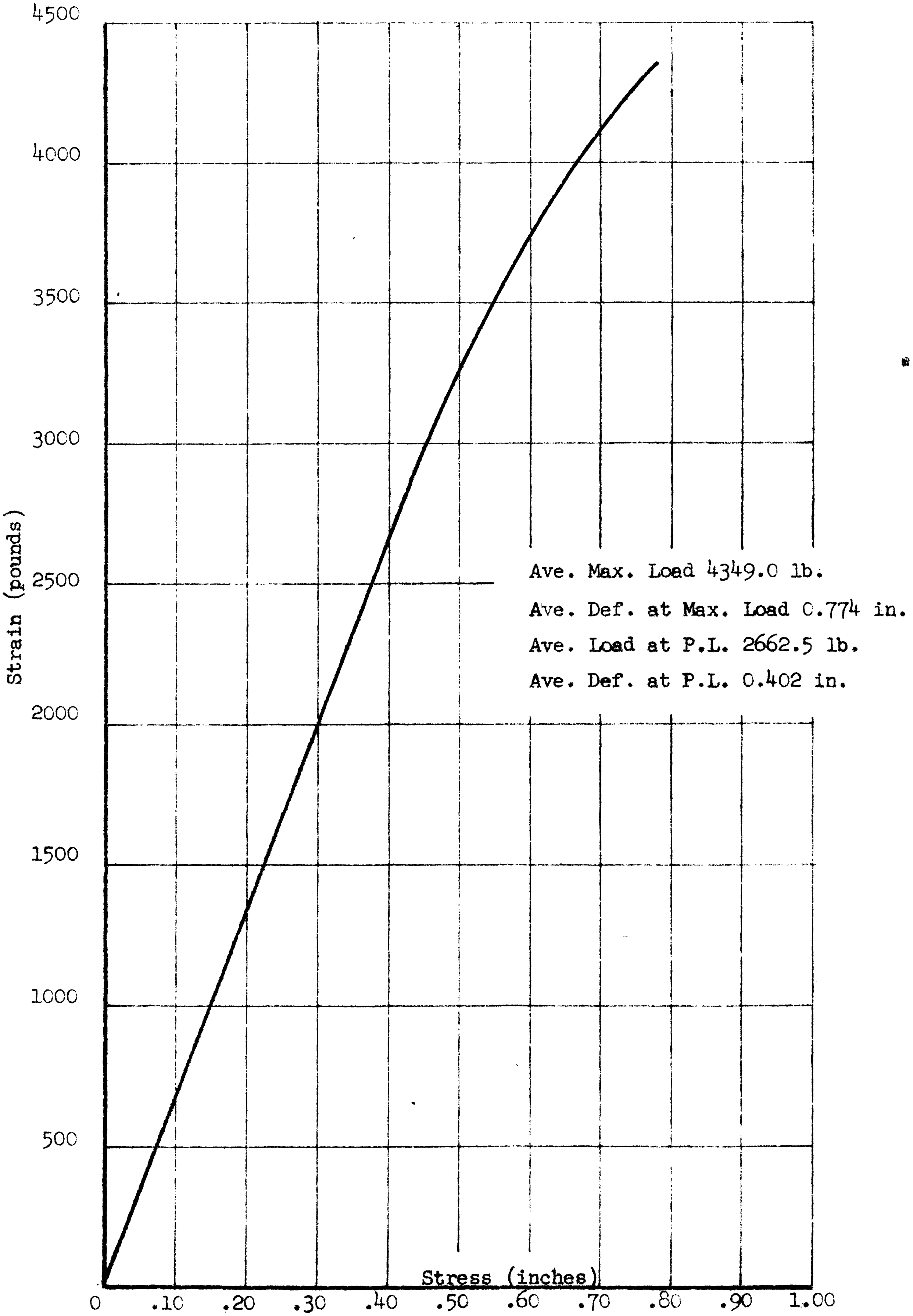


FIGURE XV

STRESS-STRAIN DIAGRAM OF AVERAGES OF THE DATA OBTAINED FROM THE REINFORCED BEAMS, TYPE D

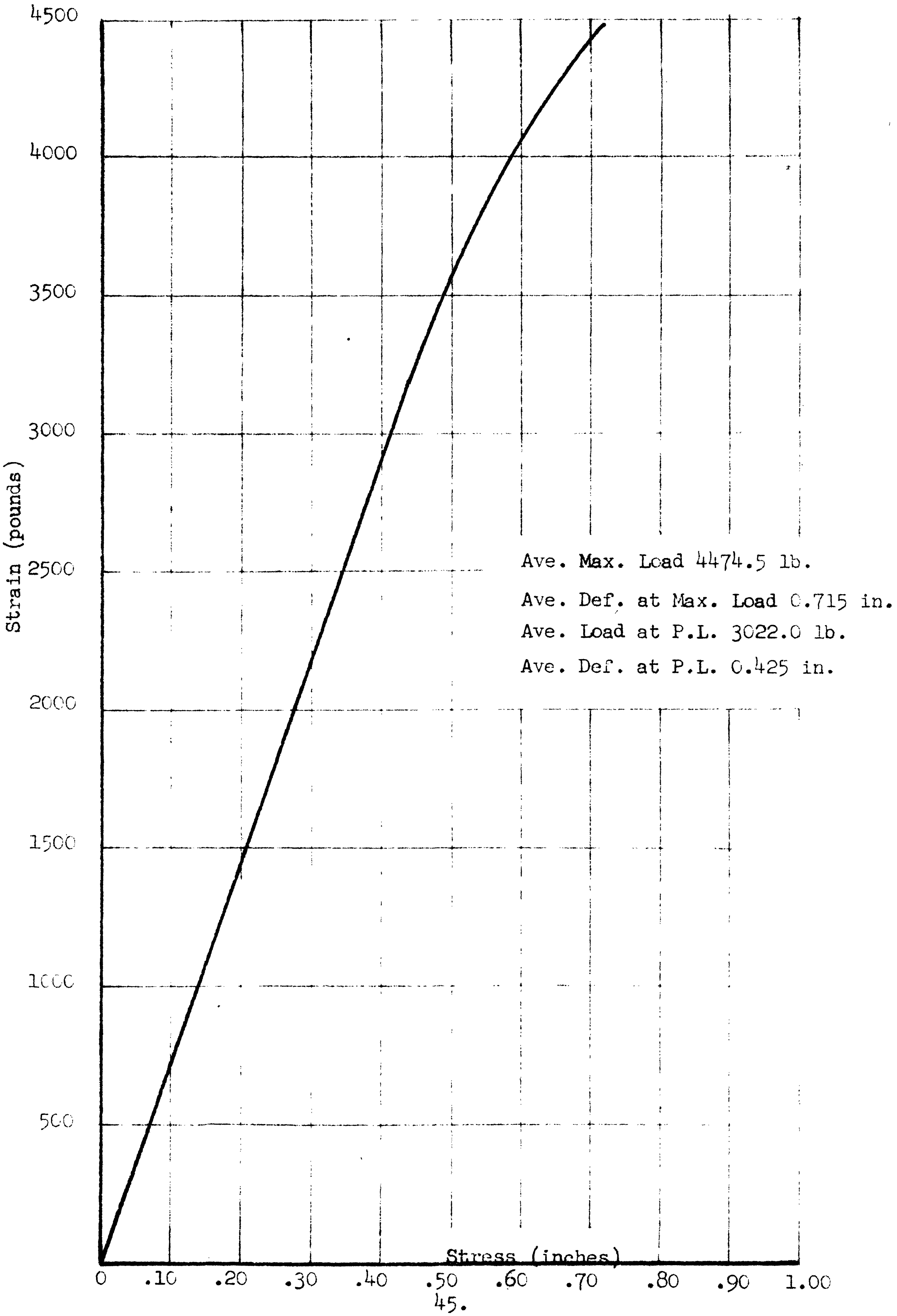


FIGURE XVI

STRESS-STRAIN DIAGRAM OF AVERAGES OF THE DATA OBTAINED FROM THE EPOXY CONTROL BEAMS, TYPE A

Ave. Max. Load 3274.0 lb.
Ave. Def. at Max. Load 0.852 in.
Ave. Load at P.L. 2219.5 lb.
Ave. Def. at P.L. 0.48x5 in.

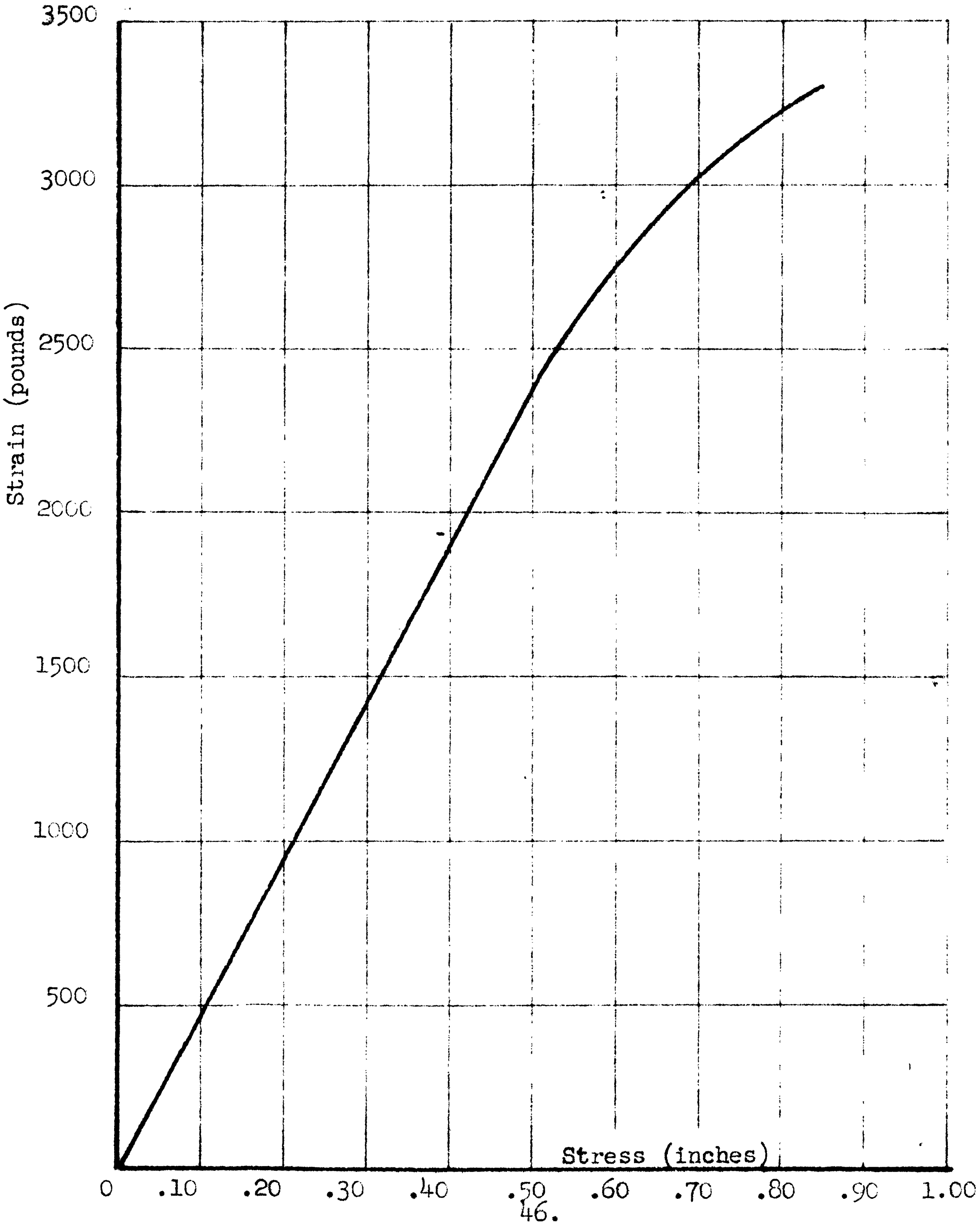


FIGURE XVII

STRESS-STRAIN DIAGRAM OF AVERAGES OF THE DATA OBTAINED FROM
THE EPOXY CONTROL BEAMS, TYPE B

Ave. Max Load 3235.0 lb.
Ave. Def. at Max. Load 0.793 in.
Ave. Load at P.L. 2239.5 lb.
Ave. Def. at P.L. 0.473 in.

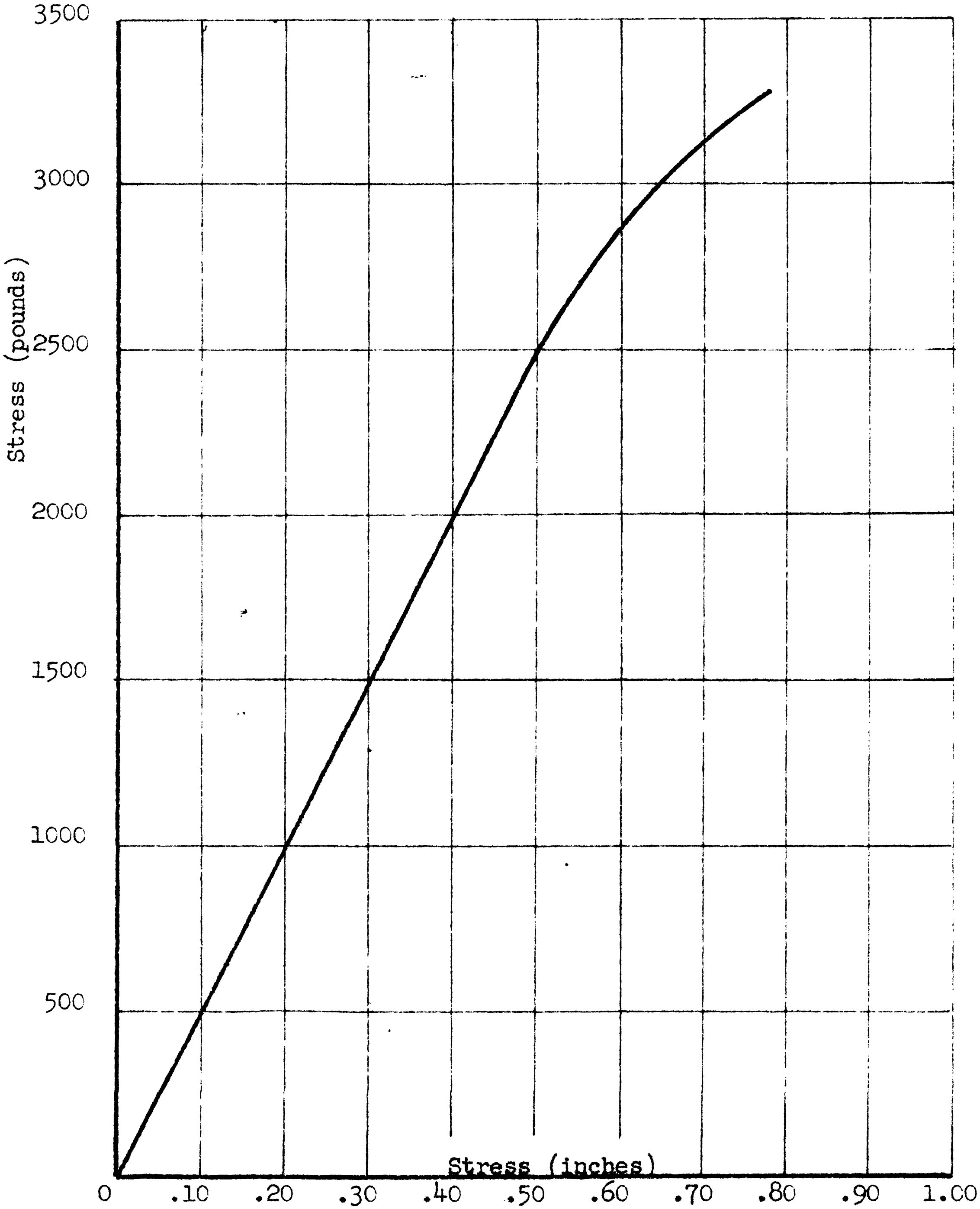


FIGURE XVIII

STRESS-STRAIN DIAGRAM OF AVERAGES OF THE DATA OBTAINED FROM THE EPOXY CONTROL BEAMS, TYPE C

Ave. Max. Load 3104.5 lb.
Ave. Def. at Max. Load 0.779 in.
Ave. Load at P.L. 2125.5 lb.
Ave. Def. at P.L. 0.457 in.

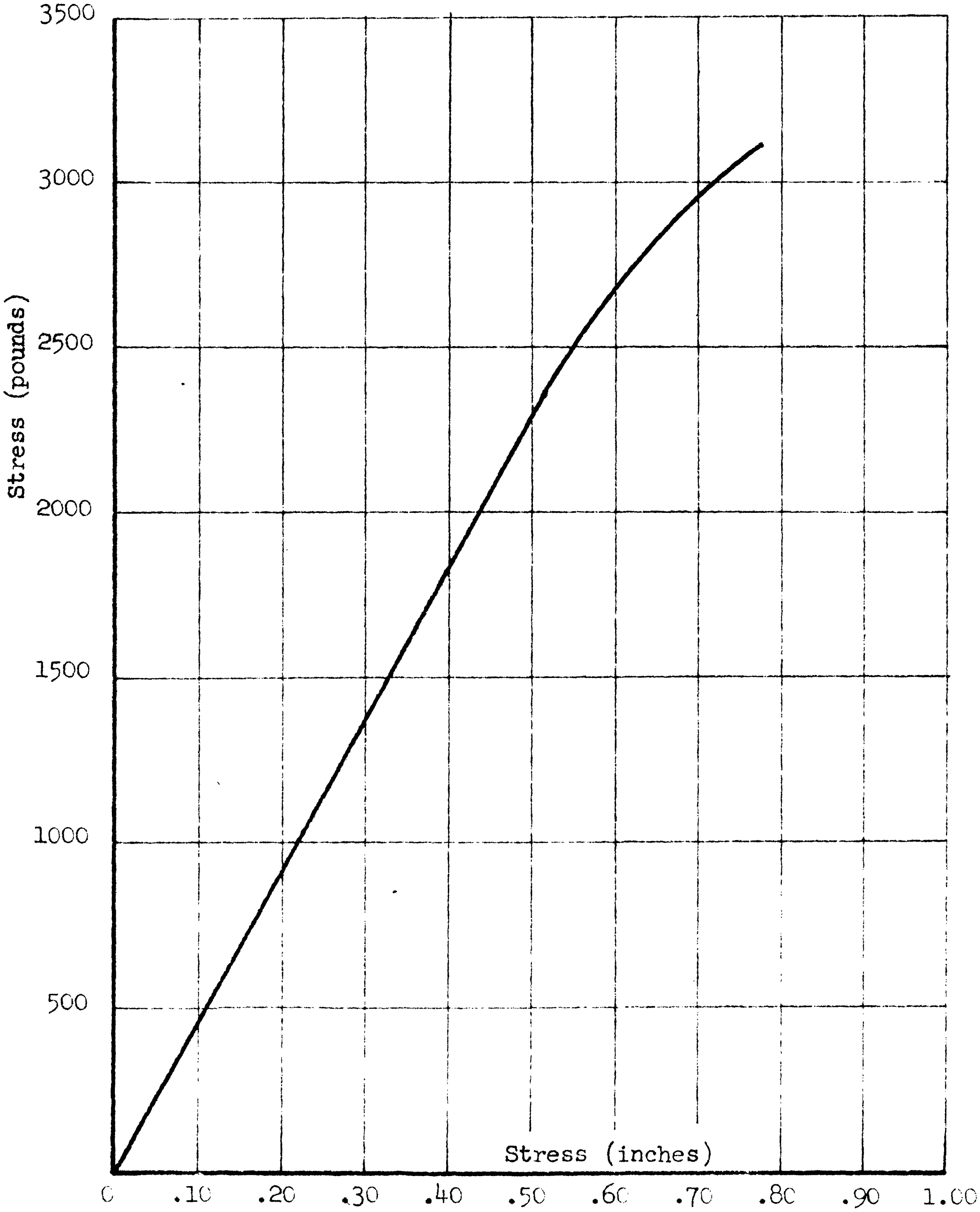


FIGURE XIX

STRESS-STRAIN DIAGRAM OF AVERAGES OF THE DATA OBTAINED FROM
THE EPOXY CONTROL BEAMS, TYPE D

Ave. Max. Load 3028.5 lb.
Ave. Def. at Max. Load 0.858 in.
Ave. Load at P.L. 1844.5 lb.
Ave. Def. at P.L. 0.42x4 in.

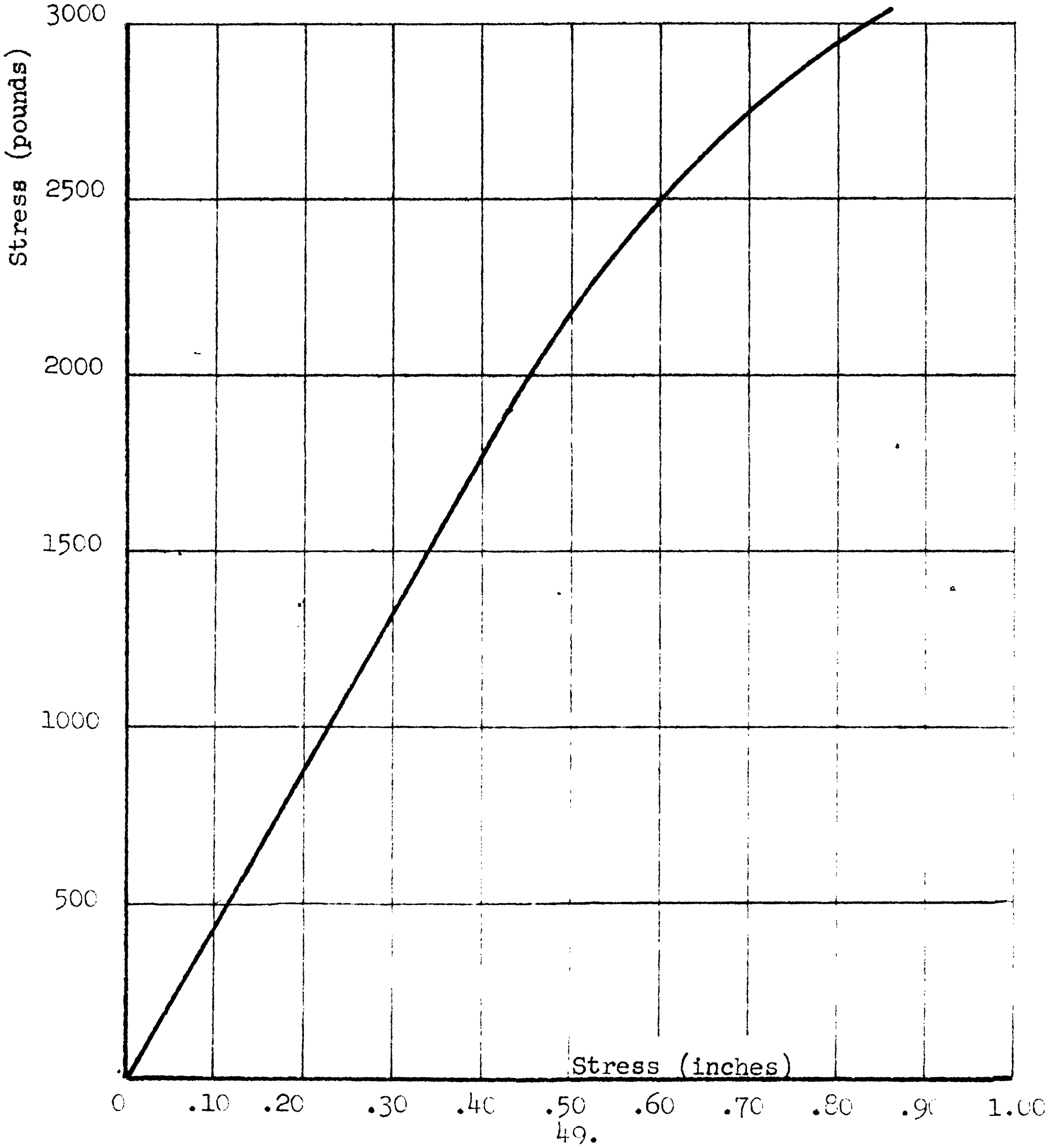


FIGURE XX

STRESS-STRAIN DIAGRAM OF AVERAGES OF THE DATA OBTAINED FROM THE RESORCINOL-PHENOL CONTROL BEAMS

Ave. Max. Load 3339.5 lb.
Ave. Def. at Max. Load 0.834 in.
Ave. Load at P.L. 2302.5 lb.
Ave. Def. at P.L. 0.500 in.

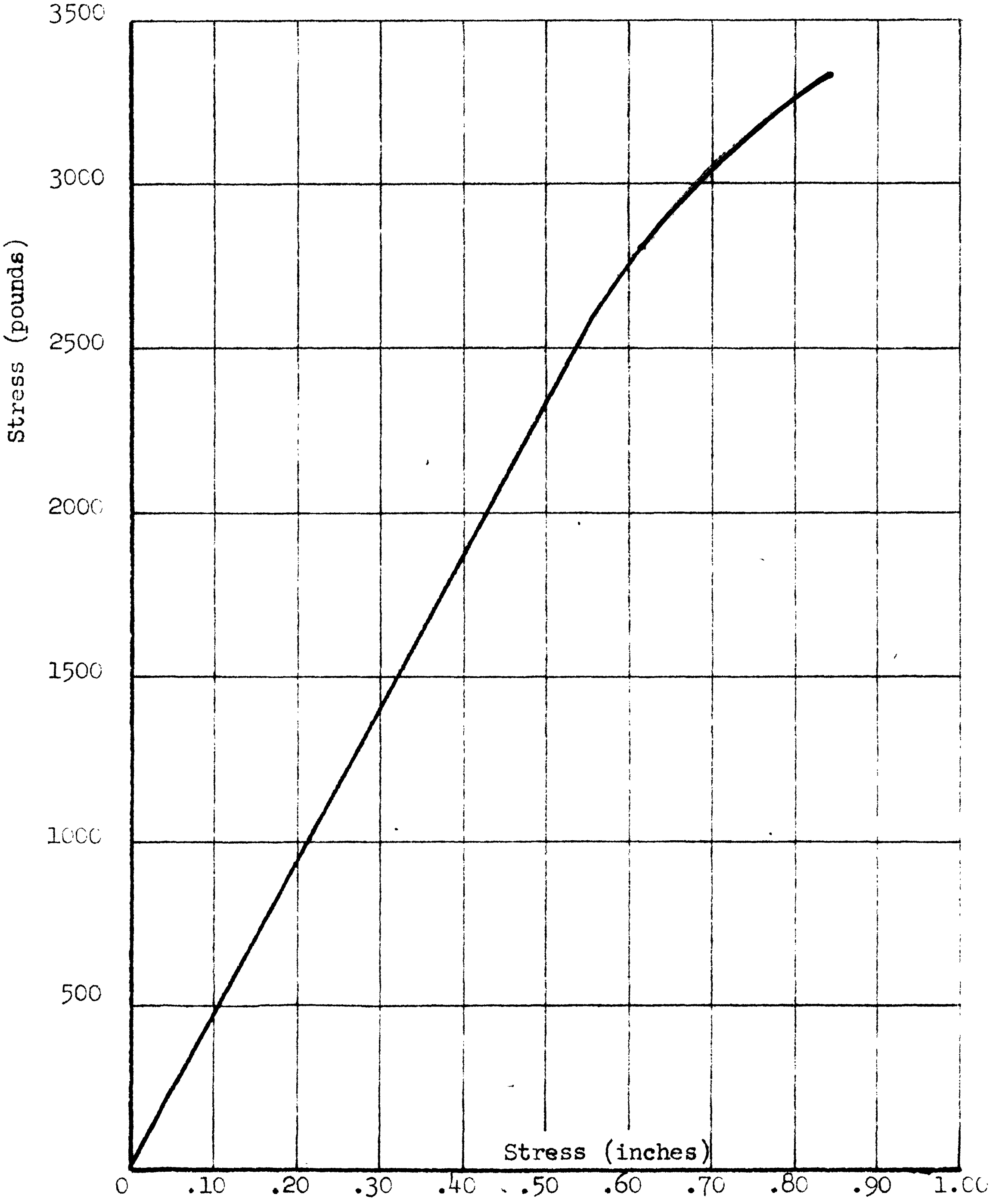
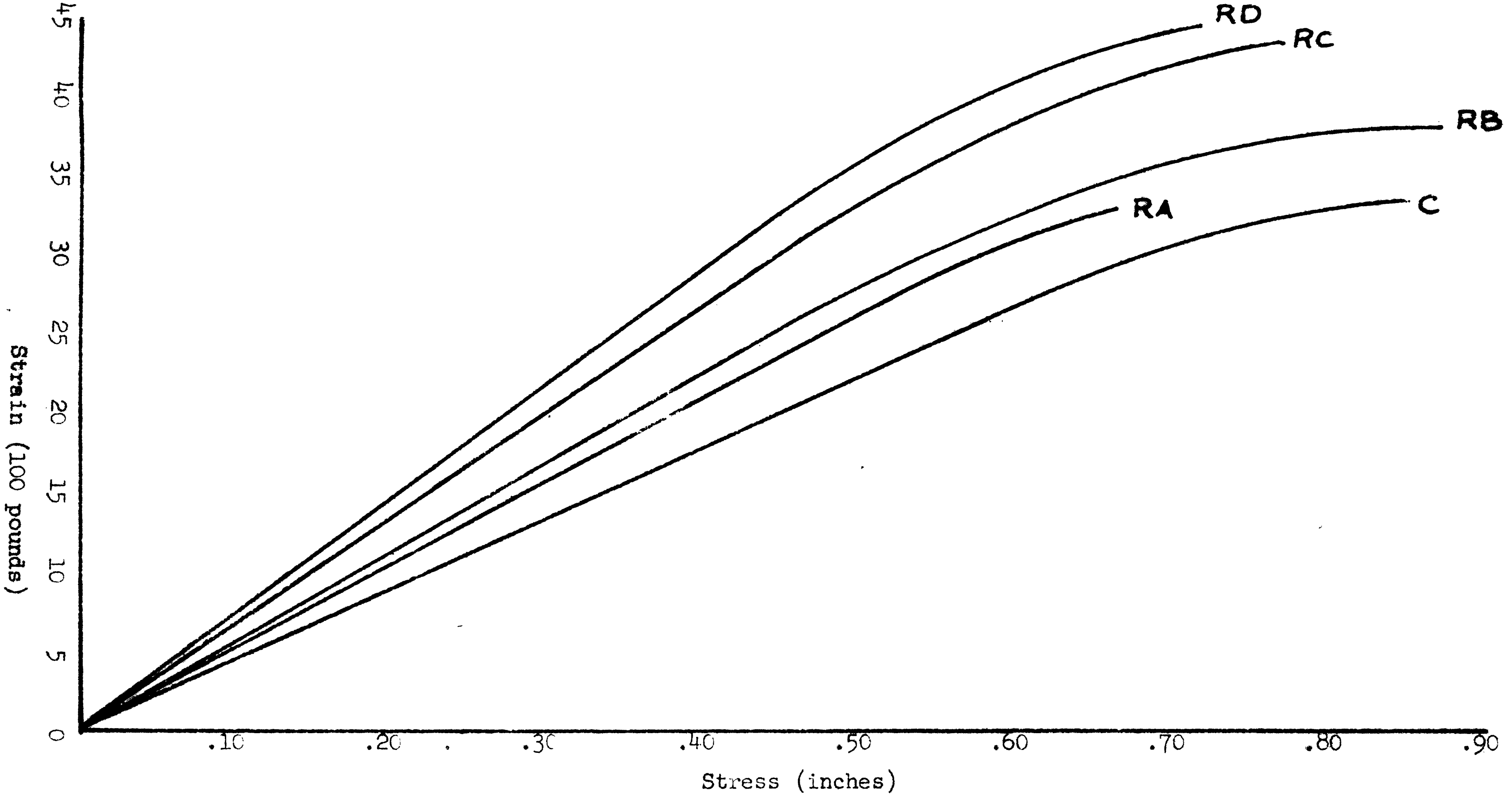


FIGURE XXI



COMPOSITE STRESS-STRAIN DIAGRAM OF AVERAGES OF THE DATA OBTAINED
FROM THE RESORCINOL-PHENOL CONTROL AND REINFORCED
BEAMS, TYPE A, B, C, AND D